

Intertidal foraminifera of the Avon-Heathcote Estuary; response to coseismic deformation and potential to record local historic events

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Frontispiece



“Nothing like a night time stroll to give you ideas” – Alastor “Mad eye” Moody

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Abstract

The Avon-Heathcote Estuary, located in Christchurch, New Zealand, experienced coseismic deformation as a result of the February 22nd 2011 Christchurch Earthquake. The deformation is reflected as subsidence in the northern area and uplift in the southern area of the Estuary, in addition to sand volcanoes which forced up sediment throughout the floor of the Estuary altering estuary bed height and tidal flow.

The first part of the research involved quantifying the change in the modern benthic foraminifera distribution as a result of the coseismic deformation caused by the February 22nd 2011 earthquake. By analysing the taxa present immediately post deformation and then the taxa present 2 years post deformation a comparison of the benthic foraminifera distribution can be made of the pre and post deformation. Both the northern and the southern areas of the Estuary were sampled to establish whether foraminifera faunas migrated landward or seaward as a result of subsidence and uplift experienced in different areas. There was no statistical change in overall species distribution in the two year time period since the coseismic deformation occurred, however, there were some noticeable changes in foraminifera distribution at BSNS-Z3 showing a landward migration of taxa. The changes that were predicted to occur as a result of the deformation of the Estuary are taking longer than expected to show up in the foraminiferal record and a longer time period is needed to establish these changes.

The second stage involved establishing the modern distribution of foraminifera at Settlers Reserve in the southern area of the Avon-Heathcote Estuary by detailed sampling along a 160 m transect. Foraminifera are sensitive to environmental parameters, tidal height, grain size, pH and salinity were recorded to evaluate the effect these parameters have on distribution. Bray-Curtis two-way cluster analysis was primarily used to assess the distribution pattern of foraminifera. The modern foraminifera distribution is comparable to that of the modern day New Zealand brackish-water benthic foraminifera distribution and includes species not yet found in other studies of the Avon-Heathcote Estuary. Differences in sampling techniques and the restricted intertidal marshland area where the transect samples were collected account for some of the differences seen between this model and past foraminifera studies.

The final stage involved sampling a 2.20 m core collected from Settlers Reserve and using the modern foraminiferal distribution to establish a foraminiferal history of Settlers Reserve. As foraminifera are sensitive to tidal height they may record past coseismic deformation events and the core was used to ascertain whether record of past coseismic deformation is preserved in Settlers Reserve sediments. Sampling the core for foraminifera, grainsize, trace metals and carbon material helped to build a story of estuary development. Using the modern foraminiferal distribution and the tidal height information collected, a down core model of past tidal heights was established to determine past rates of change. Foraminifera are not well preserved throughout the core, however, a sudden relative rise in sea level is recorded between 0.25 m and 0.85 m. Using trace metal and isotope analysis to develop an age profile, this sea level rise is interpreted to record coseismic subsidence associated with a palaeoseismic event in the early 1900's.

Overall, although the Avon-Heathcote Estuary experienced clear coseismic deformation as a result of the 22nd of February 2011 earthquake, modern changes in foraminiferal distribution cannot yet be tracked, however, past seismic deformation is identified in a core. The modern transect describes the foraminifera distribution which identifies species that have not been identified in the Avon-Heathcote Estuary before. This thesis enhances the current knowledge of the Avon-Heathcote Estuary and is a baseline for future studies.

Chapter 1: Introduction

The 22 February 2011 earthquake in Christchurch, New Zealand caused the coseismic deformation of the Avon-Heathcote Estuary (AHE). The earthquake was centred in the Port Hills to the south of the city of Christchurch causing the deformation of sediments within the Estuary. Subsidence was induced in the north, and uplift in the south of the AHE, as a result of the seismic deformation (Kaiser et al. 2012). This thesis aims to measure the response of intertidal foraminifera to the effect of the coseismic deformation caused by the 2011 Christchurch Earthquake. Additionally, this thesis aims to determine the modern distribution of foraminifera at a selected study site in the AHE to compare to a core aiding in the understanding of the foraminiferal history of the AHE.

1.1 The Avon-Heathcote Estuary/Ihutai

The area studied for this thesis is located within the Avon-Heathcote Estuary/Ihutai in Christchurch, New Zealand. The AHE is situated between the Canterbury plains and the Pegasus Bay coastline, 12 km from the city centre and has an area of 8 km² (Figure 1.1). The AHE is triangular in shape, on average ~1.4 m deep at high tide (Mean high water of ordinary spring tides) and tidally dominated (Findlay & Kirk 1988). Brighton Spit bounds the Estuary to the east, this was formed via longshore drift from sediment supplied from the Waimakariri River to the north. The southeast margin of the AHE opens to the sea adjacent to the Port Hills (Forsyth *et al.*, 2008) permitting tidal exchange and mixing of sea water with fresh water. The AHE's main fresh water inputs, as suggested by the name, are the Avon and Heathcote Rivers, both spring fed rivers which flow through Christchurch city. The Avon River enters the Estuary from the northwest and the Heathcote River enters from the southwest (Figure 1.1) (Findlay & Kirk 1988).



Figure 1.1. Location of the main study area in the Avon-Heathcote Estuary

The main site studied is Settlers Reserve at the mouth of the Heathcote River. In addition a secondary site, Bridge Street, at the mouth of the Avon River, was studied to compare samples taken from between 2011 and 2013.

The definition of an estuary differs in scientific literature, a commonly used definition is that of Pritchard (1967) “a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage”. This definition, however, does not include coastal lagoons

temporarily blocked off by sand barriers or hypersaline bodies of water where evaporation exceeds fresh water inflow (Hume & Herdendorf 1988). A broader definition by Day (1981) addresses this issue and will be used in this study. “a partially enclosed coastal body of water which is either permanently or periodically open to the sea and within which there is a measurable variation of salinity due to the mixture of seawater and freshwater derived from land drainage”.

The Avon-Heathcote Estuary is sub-classified as a dominantly fluvial erosional semi enclosed barrier-built estuary with a single spit. The Estuary has the key characteristics of a single bar dividing it from the sea (Brighton Spit), with the exception of an outlet which may shift from time to time and permits tidal exchange (Hume & Herdendorf 1988). It can also be classified as varying between a salt wedge and a well-mixed estuarine environment (Knox and Kilner, 1973).

1.1.1 Estuary Development

There is debate surrounding the age of the Avon-Heathcote Estuary, with Macpherson (1978) suggesting that the estuary is between 1000 and 2000 years old whereas Owen (1992) states that it has only existed in its current state for the past 450 to 500 years. Both of these assumptions are broad statements as estuaries are constantly changing environments and do not stay in one state for an extended period of time. Past estimated shore line's show that where the AHE is now would have been ocean 1000 to 2000 years ago but the Estuary could have featured in a different form still at the mouths of the Avon and Heathcote Rivers.

McFadgen and Goff (2005) have developed a model of the formation of the Avon-Heathcote Estuary which accounts for changes in the area over the past 4000 years. This model indicates that seismic induced avulsion of the Waimakariri River affected the development of the AHE helping it to develop into its current state. The area now known as the Avon-Heathcote Estuary began as an open bay 4000 to 2500 years before present (ybp) when the Waimakariri River was flowing between Banks Peninsula and its current location. Following this a series of earthquakes along the Alpine Fault caused an increase in sediment and the Waimakariri River channels to avulse. Between 2500 and 450 ybp the area changed between an open bay to a barrier estuary twice as excess, earthquake induced, sediment accumulated forming a barrier in front of the open bay before being eroded away after the Waimakariri River channels avulsed back into the path of the estuary (2500 to 700 ybp).

Between 700 and 450 ybp further earthquake activity caused the Waimakariri River to avulse again to the north reforming the sand barrier which continued to increase due to excess sediment. Yet another large earthquake between 450 and 470 ybp caused the Waimakariri River to avulse back to the south exiting through Lake Ellesmere and then briefly through the AHE before returning to the north where it currently resides. The Avon-Heathcote Estuary is said to be in its current form since 450 ybp correlating with Owen, (1992) although there is little consistent evidence, this theory, while only a model is still plausible.

Estuaries are highly stressed environments and species living within them need to be able to adapt to constant change. These changes such as salinity and tide variation calls for species living within estuaries to be resilient to change and results in a low diversity but high abundance of biota (Schafer et al., 1991). The Avon-Heathcote Estuary has gone through many changes induced by both natural (geological, geomorphological and biological) and anthropogenic causes, this increases stress on the estuary. The significance of some of these changes is discussed below.

1.2 Human influence

There has been anthropogenic influence over the Avon-Heathcote Estuary since the Christchurch area was settled by the indigenous Maori population; today the population of Christchurch continue to have an impact the AHE.

1.2.1 Maori hunting grounds

Indigenous (Maori) settlement of the Christchurch area is dated as around 700 to 800 years before present (ybp) when the first settlers established themselves in the South Island of New Zealand (McWelthy 2010). The introduction of people and their hunting and gathering techniques to the Avon-Heathcote Estuary and surrounding water catchment is the first sedimentary record of changes to the environment at 600 to 700 ybp (Deely, 1991). The burning of native vegetation occurred right around the South Island with 40 % of the native forest cleared (McWelthy 2010) equating to half of the low land and montane (moderately elevated) forests. This led to the extinction or severe reduction of many vertebrate species due to over-exploitation from hunting and reduction in natural habitat from forest burning as well as increased soil erosion (McGlone, 1989). In the AHE the burning off of native forest can be seen in the sedimentary record as periods of increased sedimentation due to higher run off in the catchment. This is also identified by charcoal and pollen records in the sediment. The population grew large enough, by 500 ybp that there were not enough natural resources

remaining to continue their current lifestyle leading to a change in hunting and gathering techniques and the formation of settlements or campsites on the dunes of Brighton Spit. This coupled with the increased sediment supply from hill run-off is thought to have changed the sedimentation rates in the AHE (Penny 1982; McSaveny & Whitehouse 1989).

1.2.2 Pollution of the Avon-Heathcote Estuary

The fresh water inputs into the Avon-Heathcote Estuary flow through urban areas and have been modified by human influence. The Avon River and tributaries catchment is predominantly urban and is around 85km², while the Heathcote River has a catchment of 104km² which flows through rural, hill and urban (residential and industrial) areas (Bolton-Ritchie & Main 2005). Many storm drains from around the city flow into both of these rivers while the Heathcote River had industrial effluent discharged, untreated, directly into it between 1860 and 1972 (Deely & Fergusson, 1994).

Marine pollution is defined by the Joined Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP) as “...the introduction by man, directly or indirectly, of substances or energy into the marine environment (including estuaries) resulting in such deleterious effects as harm to living resources, hazards to human health, hindrance to marine activities including fishing impairment of quality for use of sea water and reduction of amenities”. The term pollution refers to damaging effects the wastes have on the natural environment they reside in (Kennish 1996). The term contamination or contaminants is used for the occurrence of the waste inputs in the natural environment (Clark 1992). According to Clark (1992) “contamination is caused when an input from human activities increases the concentration of a substance in seawater, sediments, or organisms above the natural background level for that area and for the organisms”. The Avon-Heathcote Estuary has been influenced by anthropogenic sources of contamination such as untreated industrial waste, sewage outfall, land drainage and storm water drains (Bolton-Ritchie & Main 2005). These inflows and sediment from land runoff all contribute to a noticeable increase sedimentation rates and morphological changes in the AHE.

1.2.2.1 Heavy Metals

Three sources of heavy metal contaminants affect the Avon-Heathcote Estuary, natural sources from the surrounding catchment, tide carried ocean material and anthropogenic sources (deliberately or accidentally) (Deely & Fergusson, 1994). These are contaminants such as Chromium, Manganese, Iron, Nickel, Copper, Zinc, Lead and Silver.

Anthropogenic heavy metal contaminants have been entering the AHE since 1860 when heavy industrial production began in Christchurch (Deely & Fergusson, 1994). Prior to 1860 there was only an iron foundry, several breweries, a saw mill and a few shops. 1860 brought the introduction of coal shipments to Ferrymead creating a cheap source of energy making it an ideal place for industrial development along with the convenience of being located along the Heathcote River for easy disposal of waste. This expanded to become the main industrial centre of New Zealand between 1880 and 1925 (Deely & Fergusson, 1994).

Industrial processes caused both aerial and waterways pollution to enter the Avon-Heathcote Estuary. Work completed by Deely & Fergusson (1994) in the AHE details the heavy metal pollutants found in the Estuary's sediments, their study used five cores collected around the Estuary to determine dates and sedimentation rates using historical records. The sediments are able to be matched up across the Estuary using the units described and analysed in each core, a combination of pollen analysis and historical events were used and clearly show the differences in sedimentation rates and contamination levels since 400 to 500 years B.P. Their results show how the heavy metals found in the sediments mirror that of the anthropogenic activities which were occurring at the time of deposition. Industries which existed along the Heathcote River that contributed to heavy metal contamination were tanneries, foundries, sawmills, iron-mongers, tinsmiths, zinc works, blacksmiths, a brewery, a soap and candle factory, glue factories, brass foundries, lime kilns, the wool works, the Christchurch gas works and a battery factory. Some were short lived while others were ongoing and up to 10 million litres of waste production was pumped untreated into the AHE every day before 1971 (Deely 1991). It wasn't until 1973 that the Woolston Industrial sewer came into action and pumped the industrial waste into the Christchurch Drainage Board Treatment Plant. The Christchurch Gas Works were also a significant contributor and did not stop dumping effluent directly into the Heathcote River until it closed in 1981 (Deely 1991).

Heavy metals accumulate in sediment and this increases the concentration of these metals, grain size is shown to influence what quantity of the heavy metals gets trapped in the sediment. Finer sediment has a greater surface area and a greater capacity to hold onto heavy metals. It has been shown in a study of Cd concentrations in various grain sizes that particles finer than $2\mu\text{m}$ can hold tenfold more heavy metals than coarse grained sediment (Foerstner & Salomons, 1980).

1.2.2.2 Silting

Silt build up in both rivers flowing into the AHE is linked to the heavy drainage of the Canterbury Plains via the two major river outlets (Findlay & Kirk 1988). The increase in population lead to an increase of drainage, domestic sewers and industrial wastes into the rivers as well as increased soil runoff from horticultural land alongside the Heathcote Rivers. This build up became noticeable in the 1920's which was then mitigated against up until the 1950's by river sweeping. The river silts were swept into the Avon-Heathcote Estuary changing the estuary into mud flats with only the major estuary channels having water in them at low tide. Pre European sedimentation rates in the AHE were calculated to be 0.15 cm/yr whereas post European rates of sedimentation have been calculated as being 0.27 cm/yr in the early 1900's. During the time of mechanical sweeping sedimentation rates in the Estuary rose to 2 cm/yr but has since dropped to 0.5 cm/ yr (1990's) (Deely & Fergusson, 1994).

Silting of the Estuary from the sweeping of both rivers into the AHE affected the flora and fauna distributions as well as added nutrients from the sewage outfall pipe and heavy metals from industrial production (Findlay & Kirk 1988). Silt build up is blamed for the disappearance of the estuary grass *Zostera nana* as it could not outgrow the rate of sedimentation. The disappearance of a burrowing bivalve (*Macra ovate*) was also thought to be because it was unable to keep up with the rapid deposition of mud (Deely & Fergusson, 1994). An increase in mud was welcome by some macro invertebrates shown with the population growth of crabs (*Helice crenata*), mud snails (*Amphibola crenata*) and cockles (*Austrovelius stutchburi*) and singular species of ostracod (*Callistocythene reoplana*). An increase in nutrients from the sewage outfall pipes caused the appearance of various types of blue green algae, green slime and sea lettuce, these are commonly associated with anthropologic enrichment of aquatic environments (Deely 1991).

1.2.2.3 Geomorphology

The urbanisation of the Christchurch area influenced the shape of the Brighton Spit which has gone through erosional and depositional stages since European settlement. It is thought that the increasing volume of the tidal compartment between the late 1800's and the 1930's influenced the mouth of the AHE to widen due to increased tidal flow. The development of the McCormacks Bay Tram Causeway also contributed to erosion whereby altered drainage and helped erode Skylark Island, that in turn initiated erosional changes in the Estuary mouth between 1910 and the 1920's. Since the late 1940's the Estuary mouth has

been relatively stable and the spit has been populated with permanent dwellings. There have been local erosional events since then but the channels in the Estuary have stabilised and not changed significantly since. Changes in the Brighton Spit influenced the tidal regime and altered it to a mixed bar and tidal bypassing regime which are unpredictable and less stable than prior to 1938. These are influenced by how efficiently sediments move through the estuarine system (Findlay & Kirk 1988).

1.2.2.4 Effluent Distribution

Christchurch's sewage was originally discharged directly from the sewage ponds into the Estuary starting in 1882. The methods of treatment were basic in the beginning with settling ponds where the effluent would filter through sand and make its way into the estuary while some was spread over paddocks. Since then the treatment works have been upgraded multiple times with further treatment of the effluent. It wasn't until 1973 though that the discharge of sewage was no longer continuous but rather released on the ebb tide (Deely 1991). Sewage release over a long period of time into the AHE has had detrimental effects on flora and fauna populations in the Estuary. As of 2010 this practice has ceased and now is discharged 3 km off shore into the ocean.

1.3 Foraminifera Applications in Estuarine Environments

Foraminifera (Order: Foraminiferida) (foraminifera) are in the Phylum Protista and are unicellular protozoa enclosed in a test or shell made up of one or more interconnected chambers. There are two types of foraminifera, benthic forms which live on the ocean floor and are populous from the abyssal to brackish estuaries and planktic forms which are suspended in the water column and are mainly populous in coastal to abyssal environments. Foraminifera can live from fully marine environments to brackish marshes/estuaries and individual species are highly sensitive to their environment and specialise within these areas (Sen Gupta 2003).

Benthic foraminifera are highly sensitive to environmental factors such as salinity, sediment grain size, temperature, carbonate corrosivity and tidal height and as such are useful in marine and estuarine environments for determining past environments, timescales down cores and pollution evaluations. When changes in an environment take place foraminifera can be used as a marker to identify the changes as faunal distributions adjust to the new conditions (Murray, 2006). This becomes difficult when the original foraminifera distribution has not been previously studied in the area or the dissolution of foraminifera tests is taking

place and removing the evidence of dead assemblages. Cores collected in estuaries can give an abundance of information regarding the past environment but it is recognised that calcareous foraminifera tests have less preservation potential than agglutinated tests which can skew the data (Jonasson & Patterson 1992).

Benthic foraminifera are used in environmental monitoring in estuarine environments where pollutants are easily accumulated. Due to the community structure in which they live and their sensitivity to many environmental parameters they make good indicators of environmental health (Sen Gupta 2003). Incidences of heavy metal contamination in environments can result in malformations of foraminiferal tests as well as changes in taxonomic compositions of the assemblages (Alve, 1995). Different species have different toleration levels of heavy metal contaminants for example *Ammonia parkinsoniana* has low tolerance and will mainly be found in clean environments without malformations whereas *Ammonia tepida* are not highly affected by heavy metals and can tolerate the low quality environment (Frontalini & Coccioni 2008). These are known as bioindicators of marine environments but there are issues with foraminifera being used as such. If it is unknown what the original species distributions were like before contamination of the area then it is hard to evaluate the damage caused. The more stressed an environment becomes the lower the variability in species of the original foraminifera population (Schafer 2000).

Foraminiferal changes can be tracked in modern day cores collected from estuaries to assess the human impact on estuarine environments, the health of estuaries and study past seismic events. Changes in foraminifera from calcareous to agglutinated can be seen in areas where increased human activity has affected estuarine health. Foraminifera are sensitive to a wide range of environmental parameters such as salinity and tidal depth, changes in land use in the surrounding environment can impact on these parameters and the distribution of the foraminifera population will respond (Hayward et al., 2004b). Transfer functions can be used to determine elevation estimates of past environments down cores, surface foraminiferal data can be applied to core data to create a model. Past sudden changes in vertical displacement and increased rates of sedimentation can then be identified (Hayward et al., 2004c). Seismic histories have been established using such methods in the Bay of Plenty (Hayward et al., 2004a) and Hawkes bay (Hayward et al., 2006).

1.4 New Zealand Shallow Water Benthic Foraminifera

New Zealand benthic brackish foraminifera have been described in detail in Hayward et al., (1999). Over a period of 7 years samples were collected from brackish environments around New Zealand and a generalised model of the ecological distribution of foraminifera in New Zealand brackish-water was created. Because of the many species present in brackish environments around New Zealand the model was created using foraminiferal associations, these associations are named after the dominant species present in common groupings of foraminifera found in samples together. There are 10 brackish-water species associations identified around New Zealand as seen in Figure 1.2, these foraminifera associations are sensitive to environmental parameters and are shown in their ideal settings. This is a generalised model which fits what was found throughout New Zealand but it is expected that some differences will arise when compared to a detailed site study.

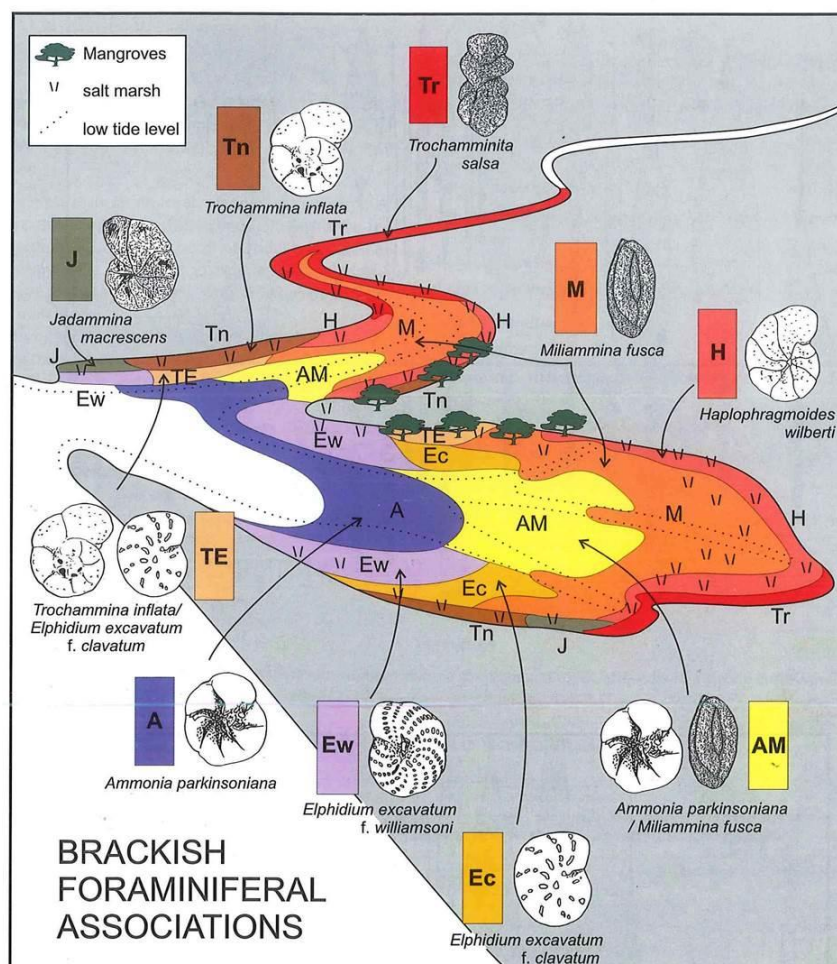


Figure 1.2 Schematic diagram showing the ecological distribution of 10 brackish foraminifera associations (Hayward et al., 1999).

There are environmental parameters surrounding where foraminifera are suited to living, there were 20 environmental factors measured to help understand the relationship of foraminifera associations in New Zealand. These include different grainsizes, tidal exposures, salinity, vegetation, and latitude; species which appear in foraminifera associations together have similar tolerances. The two environmental parameters which have the most effect on the distribution of foraminifera associations in New Zealand are tidal exposure and salinity (‰) (Figure 1.3).

Tidal exposure describes the amount of time foraminifera are comfortably exposed to above water conditions during an average tidal cycle (Hayward et al., 1999). Foraminifera species have individual ranges of tidal exposure which they can tolerate as shown in Figure 1.3, these most commonly have a predominantly intertidal range, a mixed intertidal to subtidal range or a predominantly subtidal range.

Fresh water is constantly mixing with marine water in estuarine environments causing a wide range of salinities to be experienced throughout a tidal cycle, from near fresh water salinity to near marine salinity depending on tides (Cheng et al., 2011). Figure 1.3 shows how the salinity of common brackish-water foraminifera is different for all species; these can be broadly subdivided into three main categories of low, mid and high salinity tolerance.

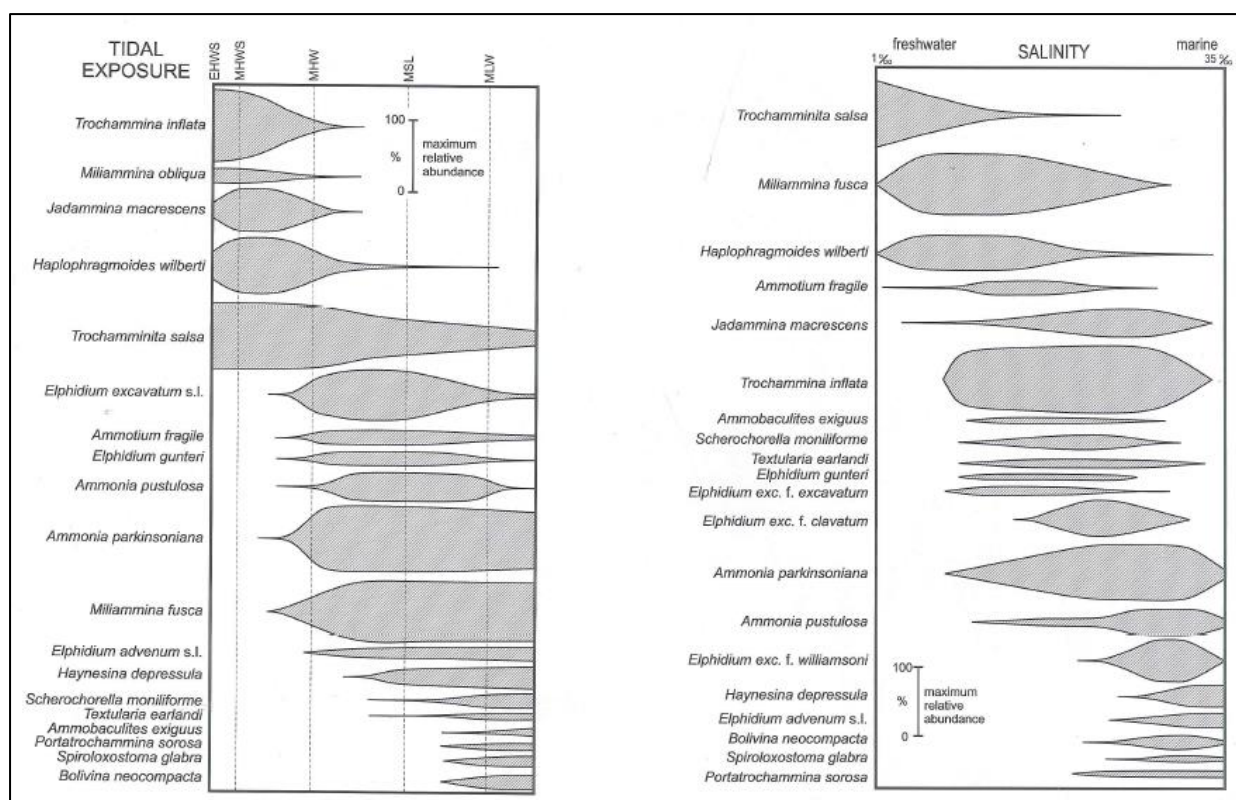


Figure 1.3 Two histograms showing different environmental parameters of brackish-water benthic foraminifera in New Zealand, on the left is a histogram of Tidal Exposure summarising the distribution of common benthic foraminifera in order of decreasing tidal exposure (EHWS = extreme high water spring, MHWS = mean high water spring, MHW = mean high water, MSL = mean sea level and mid tide level, MLW = mean low water). On the right is a histogram of Salinity summarising the distribution of common benthic foraminifera in order on increasing salinity (Hayward et al., 1999).

1.4.1 Foraminifera of the Avon-Heathcote Estuary

Past foraminiferal research in the Avon-Heathcote Estuary is limited to Pearson (2009) which aimed to describe the species diversity and distribution of foraminifera throughout the AHE. This study sampled sites throughout the Estuary (Figure 1.4) and described the species found at each sample location as well as the species associations which were present in the Estuary. Findings of this study show that there is low diversity of foraminifera throughout the AHE and there are 6 species associations present. The species associations are *Miliammina fusca*, *Elpidium advenum*-*Haynesina depressula*-*Nonionellina flemingi*, *Haplophragmoides wilberti*-*Trochammina inflata*, *Haynesina depressula*-*Zeafiorilus parri*-*Nonionellina flemingi*, *Trochammina salsa* and *Elphidium advenum*. These associations differ from those identified by Hayward et al., (1999).



Figure 1.4 Sample locations in the Avon-Heathcote estuary (Pearson 2009a).

1.5 Seismic History

The Canterbury region is located in an active seismic zone caused by the collision between the Australian and Pacific tectonic plates (Pettinga et al., 2001). Since European settlement historic records show large earthquakes have occurred in the Canterbury region in the 1800's and 1900's. Earthquakes were not able to be adequately measured up until 1942 so smaller quakes would go unnoticed and only the larger ones recorded usually by newspaper descriptions of the damage done to buildings. Modern earthquake recording techniques, however, are sensitive enough to register very minor earthquakes and earthquakes generated long distances away, these records show how active the Canterbury region (Pettinga et al., 2001).

Christchurch has a history of damaging earthquakes, there are several main earthquakes which damaged buildings and infrastructure in the 1800's and early 1900's. Far field and short field earthquakes have impacted Christchurch, the most prominent earthquakes that caused noticeable damage are the 1869 and 1870 Christchurch Earthquakes, 1881 Castle Hill Earthquake, 1888 North Canterbury Earthquake, 1901 Cheviot Earthquake and the 1922 Motuanau Earthquake (Pettinga et al., 2001). These earthquakes caused varying

levels of damage to buildings, notably the 1888 North Canterbury Earthquake which knocked the spire off Christ Church Cathedral.

1.5.1 Canterbury Earthquake Sequence

The Canterbury Earthquake Sequence (CES) commenced on the 4th of September 2010 with a magnitude 7.1 earthquake centred 30km outside of Christchurch near Darfield. It was the first major earthquake in the sequence (Bannister & Gledhill 2012) that has continued to produce earthquakes in 2014. This September 2010 earthquake resulted in widespread liquefaction and production of sand volcanoes in the Avon-Heathcote Estuary (Reid et al., 2012).

The February 22nd Christchurch Earthquake that followed devastated Christchurch City and liquefaction was even more widespread than the Darfield Earthquake (Bannister & Gledhill 2012). The shallow 6.2 magnitude earthquake with a focal depth of 10km had extremely high vertical ground acceleration (in excess of 1g) above that of the building design code and was in close proximity to the central city, these conditions combined to produce the extensive damage seen (Fry et al., 2011)

The ground motions of the February 2011 event resulted in vertical ground deformation in the wider Christchurch area (Beavan et al., 2011). The Avon-Heathcote Estuary experienced subsidence and uplift in different areas, in the north around the Avon River outlet $\sim 0.34 \text{ m} \pm 0.10 \text{ m}$ of subsidence was experienced. The southern area of the AHE around the Heathcote River outlet was uplifted $\sim 0.22 \text{ m} \pm 0.10 \text{ m}$. (Cochran et al. 2014) The Estuary was uplifted overall with an average a rise of 0.14m in elevation, this has decreased the total tidal prism volume of the Estuary (Measures et al., 2011). With the changing area in which the tides now reach, subsided areas are further inundated while in uplifted areas tides no longer reach as high as they once did, it is likely that the estuary will change in shape. With the decreased volume of tidal water it is predicted that the estuary will narrow (Measures et al., 2011).

Following the February 2011 earthquake sand volcanoes were again widespread in the AHE and then again to a lesser extent following the 6.0 magnitude June 2011 and December 2011 earthquakes (Reid et al. 2012). Sand volcanoes varied in size from large 2 to 5 m in diameter sand volcanoes to smaller 0.2 to 0.5 m in diameter sand volcanoes, these affected between 20 to 40 % of the total area of the AHE. The sand volcanoes were largely reduced in

size by tidal and wind action (Reid et al. 2012), however, the ejected sediment has been redistributed within the Estuary rather than completely removed (Measures et al., 2011).

Following the 22nd February 2011 Christchurch Earthquake untreated human sewage and household wastewater was discharged directly into the Avon River, Heathcote River and the AHE up until the 28th of October 2011. This impacted on the water quality of the Estuary elevating ammonia nitrogen levels and decreasing dissolved oxygen % saturation but not to concentrations that would impact on the maintenance of aquatic life (Bolton-Ritchie 2012). These raw sewage inputs have now ceased the levels of ammonia nitrogen and dissolved oxygen have improved (Bartram 2013).

1.6 Aims of thesis

1. To evaluate the effect of coseismic deformation on foraminifera
2. Determine if foraminifera be used to identify past seismic events in the Avon-Heathcote Estuary
3. Collect a sediment core to determine past coseismic deformation

Since the Canterbury Earthquake Sequence begun there have been evidential changes in the Avon-Heathcote Estuary. The February 22nd 2011 Christchurch Earthquake brought with it the most major changes as it induced both uplift and subsidence in the AHE.

This thesis aims to determine if foraminifera show a response to this deformation within 2 years of it occurring. Using sediment samples collected in June 2011 the species of foraminifera found will be compared to those collected in the same locations in 2013. This will quantify any change of foraminifera distribution in response to the Christchurch Earthquake.

This thesis also aims to establish the current distribution of benthic foraminifera in the Settlers Reserve intertidal zone. Using a transect laid out across the estuary in June 2013 the faunas present can be described.

The final aim is to apply the distribution of modern foraminifera to ancient faunas present in the core sample to determine the development of the southern Avon-Heathcote Estuary and identify any historic coseismic deformation events.

Chapter 2 Methods

This chapter will outline all methods undertaken in both the field and in the laboratory for this thesis. All picked foraminifera samples are stored in the Department of Geological Sciences Rock Collection.

2.1 Modern Samples

This sample collection routine for the Avon-Heathcote Estuary was set up before this student's involvement in the project and was used as part of a wider study about the effects of the February 22nd Christchurch Earthquake on the Avon-Heathcote Estuary (See Cochran et al., 2014). Samples were collected from four locations every three months starting in June 2011 and finishing in November 2013. This thesis project collected the samples in February 2013 and used the stored samples from June 2011, this sampling was completed to evaluate the change in the foraminifera species distribution as a result of the February 2011 Christchurch Earthquake. Although there were four sample locations only two of the sites were later analysed, Settlers Reserve and Bridge Street (Figure 1.1).

A detailed transect was collected in the Settlers Reserve area from the same location as the February 2013 collection of samples in the Avon-Heathcote Estuary, it was collected to establish the modern distribution of foraminifera at Settlers Reserve. The transect followed the western side of the Settlers Reserve area and ran north to south. This site was chosen specifically for detailed study because of the deformation it received in the February 22nd earthquake in particular the sand volcanoes and ~ 0.22 m of uplift.

2.1.1 Field Collection

A trowel was used to collect 1 to 2cm deep sediment surface samples at sixteen locations in the Settlers Reserve area and twenty locations in the Bridge Street area. Most foraminifera live within the top 2 cm of sediment so only surface samples needed to be collected. For the June 2011 – February 2013 comparative study sample locations were marked out with fixed pegs along two transects at both study sites, these were used during each sample collection from June 2011 onwards. Samples were taken from both comparative transects.

To collect the detailed transect a tape measure was laid out over the western side of Settlers Reserve starting at the top of the *Sarcocornia* flat. Samples were collected to

establish the distribution of foraminiferal species across the intertidal profile. In order to do this samples were taken every 5 metres for the first 100 metres of the transect and then every 10 metres thereafter for the last 60 metres due to observed homogeneity of the sediments and slope. There was no comparative transect.

2.1.2 Laboratory Preparation

In the University of Canterbury Sediment Laboratory samples were prepared for analysis. The first step was to subsample sediment and geochemistry samples from the bulk samples before processing the sediment for foraminifera.

The Rose Bengal method was used for staining samples and is adapted from Murray (2006). The stain adheres to protein based material to enable the living foraminifera to be differentiated from the dead foraminifera at the time of picking. To make up the stain 1 g of Rose Bengal was used per litre of distilled water. Samples were soaked in the Rose Bengal mixture for 24 hours giving it time to adhere to the living material. There is a chance for false positives to be recorded due to some dead foraminifera tests retaining un-decayed protoplasm (Murray & Bowser, 2000). To avoid this live samples were noted if the apertural area of the foraminifera was stained (Figueira et al., 2012).

After soaking, the sediment samples were rinsed through a 63µm sieve making sure that all mud was sieved out of the sample and all residual dye is rinsed out. Rinsing the samples makes it easier to find foraminifera in under the microscope. Samples are placed in the oven at 60°C until completely dry then transferred into labelled bags (Murray, 2006).

2.1.3 Sediment Sizing

A Saturn Digisizer II 5205 V1.01 (Digisizer) was used to analyse sediment particle size distribution. The Digisizer is a laser diffractometer that detects the range and distribution of particles ranging from 40 nanometres to 2.5 millimetres. All unprocessed sediment samples taken at each sampling stage were run through the Digisizer.

The Digisizer was run to the Fraunhofer model and 3 repeated runs were done to check the result was replicable. Obscuration limits were below 0.01 % before a sample was added. Sediment from a sample was then slowly added to the Digisizer until the obscuration level was between 15 and 16 %. The Digisizer then analysed the sample three times and the results from each run were labelled a, b, and c. These results are saved in Microsoft Excel,

PDF and summaries are presented in Appendices B and C. The percentage of each grainsize class sand, silt and clay is compiled and presented in Chapters 4 and 5.

2.2 Transect Profile

A height profile of the Settlers Reserve area was made using a Trimble Real Time Kinematic satellite positioning unit (RTK) to measure height changes (relative to sea level) and create a cross section of Settlers Reserve. This data was collected to compare the locations of the transect sediment samples to the height profile, this aids in the understanding of the distribution patterns of foraminifera from some samples. For example places where remnant sand volcanoes show up on the transect profile the samples taken from these locations are likely to contain less foraminifera than other areas.

The RTK unit is accurate to 1 cm allowing the unit to capture small changes in elevation. The RTK unit first has to be connected to a nearby GPS reference station; measurements are then collected in relation to the height difference between the known height of the reference station and the measurement location. The more satellites the RTK unit is able to connect to the more accurate the data collected on average between three and nine satellites were in use.

The measurements were made along the same transect line as in Section 2.1.1. Measurements were taken at 1 m intervals to gather a general profile on flat areas. If visible features were present such as, the relic berm, berm, small channels and sand volcanoes then measurements were taken at smaller intervals in order to capture an accurate shape in the profile.

The data from the RTK unit was transferred via the Trimble software to a Microsoft Excel file. In Microsoft Excel the data was able to be manipulated, instead of each measurement being in relation to the height of the GPS reference station it was expressed relative to sea level. To do this 9.043 m was taken away from each of the original measurements to accommodate for the elevated GPS reference station. Using Microsoft Excel graphs were able to be generated that represented a profile of the Settlers Reserve area. Using Arc Map, a geo-referenced map of the area, showing the location of the sample transect, was generated.

2.3 Core Collection

A core was collected to determine the developmental and foraminiferal history of the southern Avon-Heathcote Estuary, as well as any coseismic deformation events. The transect and core were located in Settlers Reserve, where uplift occurred in 2011, to complement a transect and study by Hayward et al. (in prep) in the Bridge Street area.

2.3.1 Field Collection

An Eijkelkamp bi-partite gouge auger set was used to collect a 2.18 m length core from the southern end of the AHE. Two different sized augers were used in the coring process, the wider 6 cm diameter auger was used for the top 1.5 m of sediments and the thinner auger (2 cm diameter) was used for the lower 0.68 m of sediments. Each auger has a 50 cm length and multiple extension rods so sediment can be sampled up to 5 m deep.

The core was taken 55 m along the same transect line as in Section 2.1.1 this is just below the *Juncus* berm. The corer was operated by two people at a time as the sediment was difficult to cut through. The corer was pushed into the ground up to the top of the sediment catcher and the handle was turned in a clockwise direction to cut core. Turning the handle cuts a clean cylinder of sediment and entraps it in the catcher; the corer is then able to be pulled out of the ground without disturbing the sediment. Before the core is removed from the ground the extension rod is marked at ground level, this mark is then used as a measuring point from where 50 cm is measured up the rod and marked again, this then tells the auger operators how far to push the corer down on the next run before pulling it up. The corer was scraped between samples to reduce contamination of the following core section.

Coring continued until the sediment was too hard for the corer and operator to penetrate. Each retrieved section of core was carefully wrapped in plastic and each end was labelled with the corresponding depth measurements and placed into PVC half pipes to transport back to the laboratory for detailed description.

2.3.2 Laboratory Preparation

The core was laid out in the Sedimentary Laboratory in the Department of Geological Sciences, University of Canterbury, photographed and described in detail. The core was then subsampled for foraminifera, sediment sizing, geochemistry and total organic carbon (TOC). These samples were taken at every sedimentary change or at 10 cm intervals, whichever occurred first. In the top 1.5 m of core, where core diameter was 6 cm, the samples taken

were 3 cm in length, 2 cm was used for foraminifera sampling and the other 1 cm was split up for sediment sizing, geochemistry and TOC work. In the lower 68 cm, where core diameter was 2 cm, the samples taken were 7 cm in length, 4 cm was used for foraminiferal sampling and the other 3 cm was split up for sediment sizing, geochemistry and TOC work.

2.3.3 Core Dating Preparation

Material suitable for dating was also sampled from the core. Organic material that appeared to be *in-situ* was sampled from 0.75 m and 2.09 m down the core, the material was removed carefully with tweezers and placed into labelled individual plastic sampling vials. At 2 m down the core a 2 cm (5 g) section of sediment was sampled for bulk carbon dating, this was placed in a labelled plastic sample vials. The organic sample at 0.75 m and the bulk carbon sedimentary sample at 2 m were both sent to Accelerator Mass Spectrometry Lab Accium Biosciences where they were analysed. As it was anticipated that the core may only reflect a few hundred years sedimentation and only two samples were sent away for radiocarbon analysis to test their reliability in this core.

2.3.4 Foraminifera and Sediment Sizing Preparation

The samples for foraminifera were prepared in two slightly varying ways. The samples in the top 20 cm were prepared using the same Rose Bengal method used in Section 2.1.2, this captures any possible live foraminifera below the surface sample. The samples below this were not treated with Rose Bengal but followed the remaining part of the foraminifera preparation method of sieving and drying. The sediment sizing samples were analysed using the same method as in Section 2.1.3.

2.3.5 Trace Metal Analysis

The sediment samples taken from the core for geochemistry were placed in aluminium trays and oven dried at 70 degree Celsius for a minimum of 72 hours. Drying at 70° C removes pathogens present in the sample but does not impair the geochemistry results. Samples were then crushed using a porcelain mortar and pestle. Following this the samples were sieved through a 2 mm stainless steel sieve to remove any large organic material and stored in plastic vials for subsequent analysis.

For each sediment sample, 1 g was weighed into acid washed digestion tubes out and 4mL of Nitric acid (HNO₃) (8N) and 10mL of HCL (2N was added). The samples were then heated at a temperature of 95 degrees Celsius for 40 minutes and left to cool overnight and

made up to 20 mL using ultrapure water. The samples were then diluted 21 times by adding 10 mL of 2 % HNO₃ to 0.5 mL of the digested sample and shaken 17 times. These samples were then analysed by Inductively Coupled Plasma Mass Spectrometry (ICP-MS) run by Rob Stainthorpe.

Quality control measures to ensure the accuracy of the results included analysis of blanks, duplicate samples and a certified reference material (CRM), this research used CRM #2702 a marine sediment. The recovery percentage for metals from the CRM was calculated to assess the accuracy of the results using the mean concentration of the two CRM samples, these results were deemed accurate.

Table 1 Percentage recovery of the CRM

Trace Metal	Percentage Recovery
Vanadium	68 %
Chromium	70 %
Iron	71 %
Manganese	83 %
Cobalt	78 %
Nickle	75 %
Copper	86 %
Zinc	78 %
Arsenic	89 %
Silver	109 %
Cadmium	106 %
Antimony	84 %
Lead	93 %

2.3.6 Carbon and Nitrogen Preparation

The core was sampled for total organic carbon and nitrogen percentages and $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$, these samples were prepared in the same way as Section 2.3.5 until sieving. After this the samples were put into separate labelled plastic vials and then taken to the Stable Isotope Biogeochemistry Laboratory at the University of Canterbury. Here they were analysed using a modified technique from McCrea (1950). The sediment samples were reacted at 70°C with 100 percent phosphoric acid in sealed reaction vessels flushed with helium gas. Using the

Finnigan Gas-BenchII the headspace was sampled for evolved carbon dioxide and then the isotopic ratios were measured using the Finnigan Delta V+ spectrometer. The carbon isotopic ratios are precised to ± 0.2 per mil using the carbonate standards NBS-19 and NBS-18 as well as the Merck internal carbonate standard.

2.4 Microscopy

2.4.1 Sample Splitting

The collected samples had too much sediment to be viewed all at once; smaller trays of sediment were looked at under the microscope making viewing easier. In order to ensure a random selection of sediment a small sediment splitter was used. This process halves the sediment until the sample is small enough to make one layer of randomly sored sediment across the tray.

2.4.2 Heavy Liquid Separation

Initial sample surveys identified samples with low foraminifera counts and these samples were floated using the heavy density liquid lithium heteropolytungstates (LST). This process separates the sediment using the different densities of the sediment and the foraminifera, the heavier density quartz sinks in the solution and the lighter density foraminifera float. The LST was calibrated to a density of 1.59.

Into a beaker 100 mL of LST was measured out and then poured into a small bowl. Around 20 grams of sediment was prepared using the sediment splitter. A funnel was set up using a clamp and stand and filter paper lined the funnel while a beaker was sat underneath the funnel to catch the drippings. The sample was then scattered evenly across the surface of the bowl of LST and the floating material immediately decanted off into the funnel. The remaining LST and sediment was stirred up to re-float any foraminifera that may have sunk with the heavier sediment, the refloated material was also decanted off into the funnel. The LST dripped through the filter paper and accumulated in the beaker. This pure LST was then recycled and used for the next sample. The remaining sediment in the funnel was then rinsed with deionised water three times to wash out any remaining LST. These washings were then saved in a new beaker to be processed back into LST form. The remaining sediment and LST in the bowl were poured out into a new filter paper and rinsed out three times. Both filter papers were then dried in an oven and the sediment poured into separate small zip lock bags and labelled as “float” (to be picked) and “sink” as a standard sample.

2.4.3 Foraminifera Picking

Foraminifera were picked using in two methods, the random square method and the whole sample method. If a sample had enough foraminifera present that it didn't need to undergo the heavy density liquid process then the random square method was used. The tray used to sort through sediment under the microscope was split up into forty five squares; each square was assigned a number from one to forty five. Using Microsoft Excel a list of thirty non-repeated random numbers was generated, each number generated correlated to one of the squares assigned number. Only the squares whose numbers were randomly generated were searched for foraminifera. All foraminifera found in the searched squares were picked out of the sediment and kept as data. This method used multiple trays of the same sample until one hundred foraminifera were found. One hundred foraminifera was the target number for each sample as this number gives valid statistically significant results for the samples. One hundred individuals was also an adequate number to record all important species. This method was carried out to reduce the amount of bias in picking (Hayward et al., 1999). Raw data was normalised into percentages to eliminate any small discrepancies in the number of foraminifera picked for each sample.

The whole sample method was used for those had been through the heavy density liquid method. The size of the sediment sample that was made up of the lighter floating material was small enough to search in its entirety. All forty five squares were searched in this method as there were fewer foraminifera in these samples making it difficult to find enough for the sample to be statistically relevant. Once the sample was searched, if fewer than one hundred but more than fifty foraminifera were found then the heavy density method was repeated and the resulting sample re-searched, this ensured finding a statistically relevant number of foraminifera. If less than fifty foraminifera were found then the heavy density liquid process was not repeated as it was deemed inefficient to repeat this process more than twice. A few exceptions to this method were found, if a "floated" sample had large amounts of foraminifera present, too many to pick all of them out of the sediment, the random square method was then applied.

Regardless of which of the above methods were used picking the foraminifera out of the sediment and onto a cardboard viewing slide was completed in the same way. Slides were covered in two coats of Gum Tragacanth to enable the foraminifera to stay on the side and then covered over with a glass cover once finished. A thin paint brush was used containing

only a few bristles; this was dipped in deionised water and twisted to make one smooth brush. Using a microscope, the paint brush was then delicately touched to foraminifera which would stick to the wet paint brush and then placed on the slide. Once all foraminifera were on the slide, using the microscope, they were identified and sorted by species.

2.5 Identification

Benthic foraminifera were primarily identified using Hayward *et al.*, (1999) and planktic foraminifera identification was completed using Hornibrook *et al.*, (1989).

2.6 Data Analysis

Samples were analysed using a range of programmes, these were Microsoft Excel, PAST and C2. The living foraminifera were left out of analysis and only the dead foraminifera were used. The dead tests were used to show long term change in the AHE and living tests are not suitable for this analysis (Murray, 2006).

2.6.1 Microsoft Excel

Microsoft Excel was used for the analysis of samples comparisons. Paired Two Sample for Means T-Tests were used to find the similarity between samples collected in June 2011 and February 2013 and graphs were made using this program to find statistical significances between samples.

Species Richness is the number of species present in a sample, this was compared between the June 2011 and the February 2013 samples to identify change over time. A significant change in mean site species richness ($p < 0.05$) for all species was tested for by performing a two-tailed one-sample t-test on the change in mean site species richness between the June 2011 and February 2013 measurements.

Species Abundance is the number of individual tests per species; this was calculated for each sample then compared between June 2011 and February 2013 to identify change over time. Pearson's correlation was calculated by finding the R^2 value of the trend line then the $\sqrt{R^2}$, this indicated whether there was any significant change in species abundance between June 2011 and February 2013 ($p < 0.05$).

2.6.2 Palaeontological Statistics

Paleontological Statistics (PAST) (Hammer et al., 2001) was used for quantitative multivariate cluster analysis and detrended correspondence analysis of transect and core data. Using the normalised data this program creates dendrogram classifications by grouping together samples with similar environmental parameters to show sample relationships. Species diversity indices were also calculated using PAST to compare diversity between the samples from this study and also to compare with Hayward et al., (1999). The transect and core samples were treated differently, transect samples containing less than one hundred foraminifera tests were disregarded as only five of the twenty seven samples did not. Core samples, however, yielded very low quantities of foraminifera tests, only six of the twenty three samples contained enough foraminifera to generate one hundred tests for statistical significance. In order to analyse the core all samples containing thirty or more tests were included in analysis, nine samples could then be used in analysis.

Cluster analysis was produced using two way, paired group Bray-Curtis distance, this produced a dendrogram from which sample associations and species associations could be gauged. Detrended correspondence analysis was produced using a reciprocal averaging algorithm as developed by Hill & Gouch (1980) this produced a graph of species and samples groupings, the axes were correlated with environmental factors which influenced the groupings.

Species diversity calculations were calculated in PAST. These diversity indices were chosen so the results could be compared to Hayward et al. 1999:

Fisher Alpha Index: $\alpha = N(1-\chi)/\chi$ (read from Murray, 1991) N is the number of individuals in a sample and χ is the number of species.

Shannon Weiner: $H_{(S)} = - \sum P_i \log_e P_i$ P_i is the proportion of the i th species while H depends on a combination of evenness and the number of species present (Gibson & Buzas, 1973).

Evenness: $E = e^{H/S}$ S is the number of species present, this only measures the evenness of the species present and does not take into consideration the number of species present (Zar 1999).

2.6.3 C2

C2 was used to create a model of the past tidal heights for the core. This process is described in detail in Section 5.5.

Chapter 3 2011 to 2013 Foraminiferal Comparison

Chapter 3 compares changes in the distribution of foraminifera as a consequence of the February 2011 earthquake which resulted in the deformation of the Avon-Heathcote Estuary. Samples were collected every three months from four different sites around the AHE (Cochran et al. 2014). Two sample sites were studied in this thesis; Bridge Street in the northern section of the AHE where subsidence was recorded and Settlers Reserve in the southern section of the AHE where uplift was recorded (Figure 3.1). The aim of this research was to track any changes in foraminiferal distribution over the two year sampling period (June 2011 to February 2013) and quantify any shift in the distribution of foraminifera. Cochran et al., (2014) set up two fixed transects at each site and foraminifera samples were collected, counted and identified using the methods stated in Sections 2.1, 2.4 and 2.5.



Figure 3.1 Map showing the location of the two sampling sites, Bridge Street in the north and Settlers Reserve in the south.

3.1 Settlers Reserve Site

The Settlers Reserve foraminiferal samples were collected along a western and an eastern transect. The map in Figure 3.2 shows the two transects divided into vegetation zones represented by different coloured points (see Cochran et al., 2014). There were eight samples collected along each transect (Z+1 to Z6).

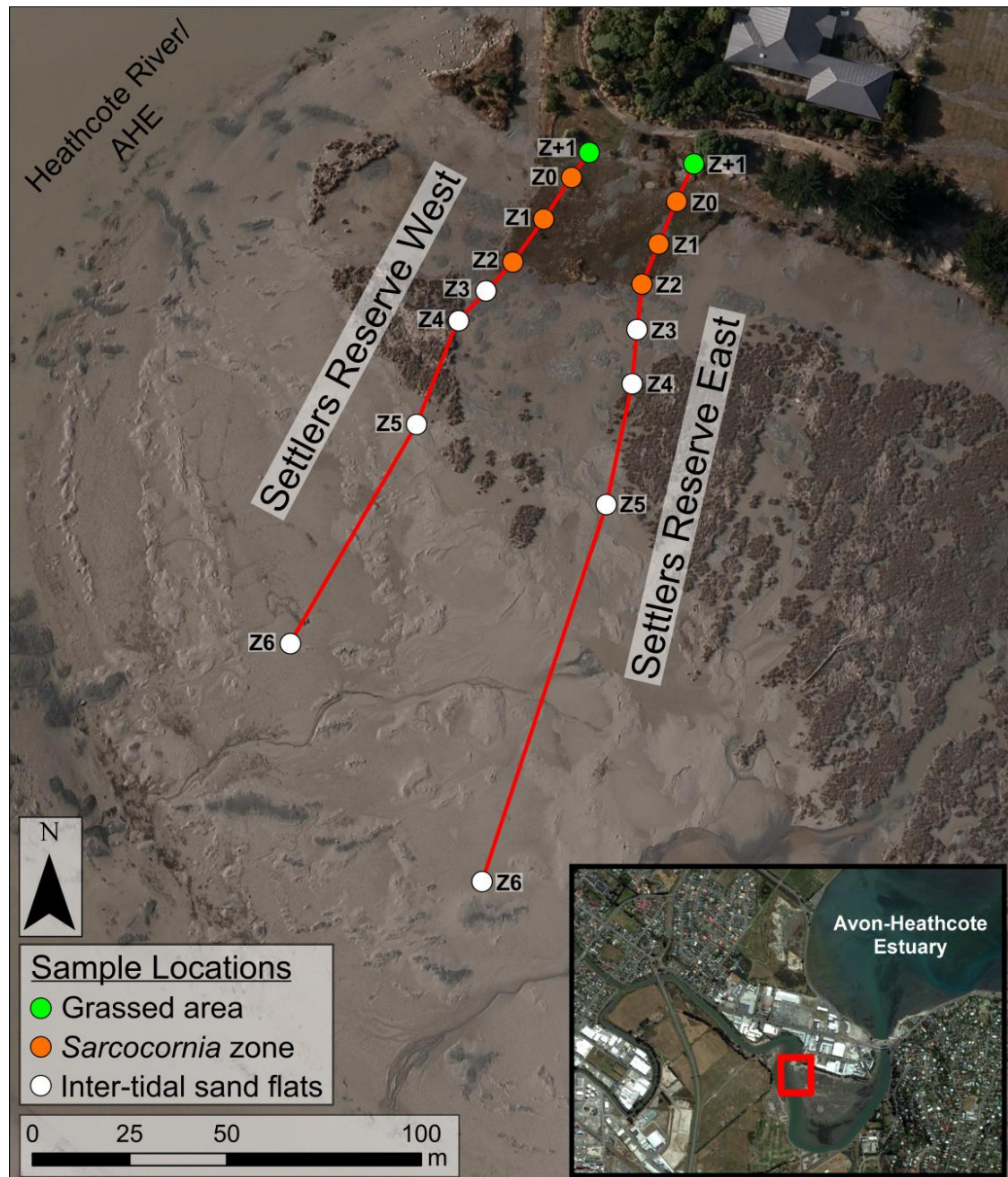


Figure 3.2 Map showing the eastern and western transect lines at Settlers Reserve sample site (Adapted from Cochran et al., 2014)

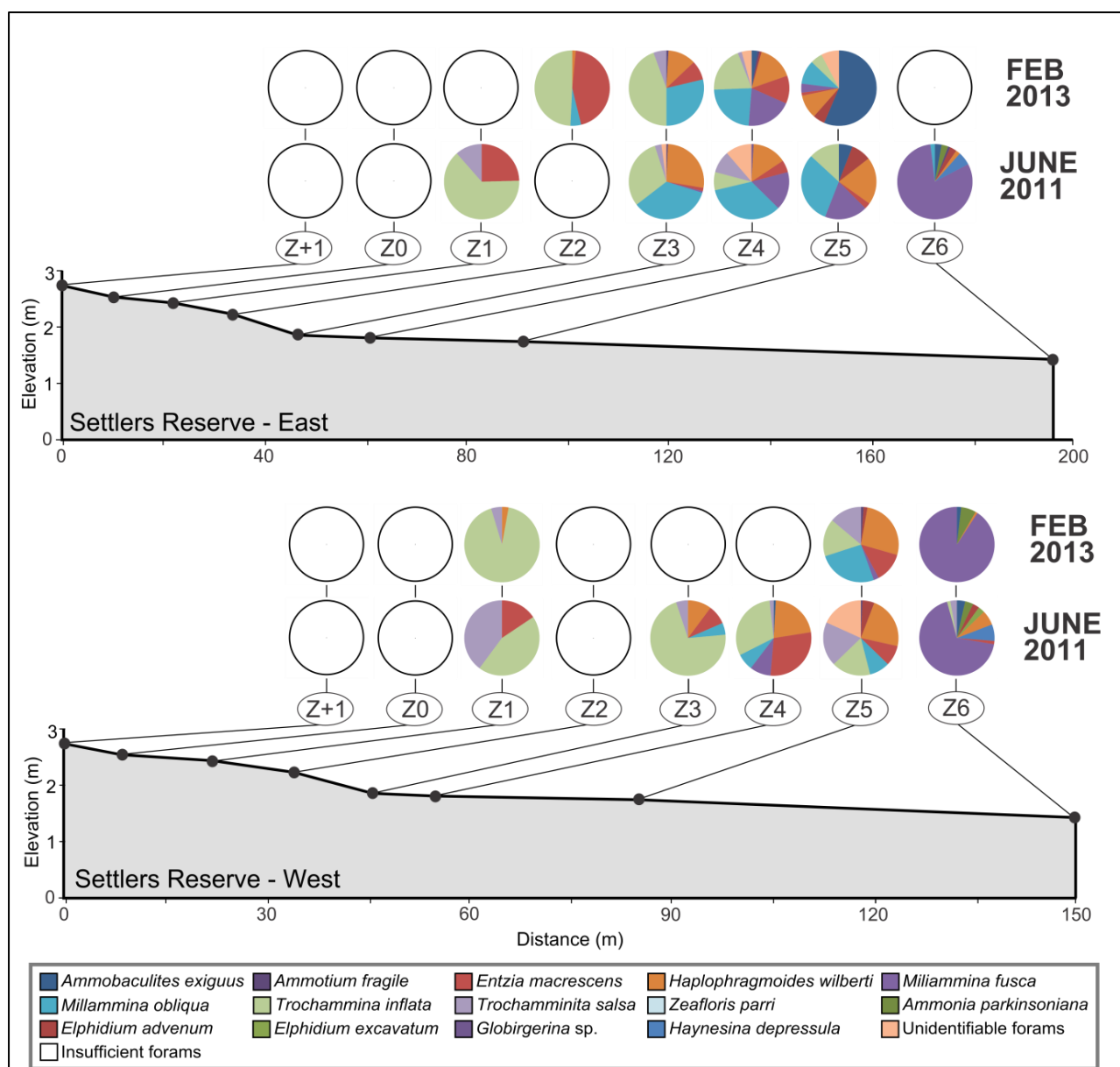


Figure 3.3. Profiles of the east and west transects at Settlers Reserve showing the sample locations. Pie graphs show the normalised species data from June 2011 and February 2013. (Adapted from Cochran et al., 2014)

3.1.1 Foraminifera Changes at Settlers Reserve

The changes in foraminifera between the June 2011 samples and the February 2013 samples are shown in Figure 3.3 and Appendix A. The pie graphs represent the proportion of each foraminifera species present at the different sampling sites from the June 2011 and the February 2013 samples. Samples with less than one hundred foraminifera picked were not included in analysis so some sites do not have a sample equivalent for comparison. Coseismic uplift has occurred at Settlers Reserve (Cochran et al. 2014) so seaward migration of intertidal foraminifera might be expected.

Only three sites were able to be compared along the eastern transect at Settlers Reserve, SRE-Z3, SRE-Z4 and SRE-Z5 while all other zones either had no foraminifera present in both years or only foraminifera present in one year. The samples SRE-Z3 and SRE-Z4 show very similar proportions of each foraminifera species between the years, although there are some small differences in percentages. Sample site SRE-Z5, however, shows high variation in foraminifera distribution between the two years, notably the much higher percentage of *Ammobaculites exiguus* and the much smaller percentages of *Miliammina obliqua*, *Miliammina fusca*, *Trochammina inflata* and *Entzia macrescens* in the February 2013 sample than the June 2011 sample.

The planktic foraminifera species *Globirgerina* sp., of marine origin, was found at sample site SRE-Z4 in the June 2011 sample. Marine foraminifera are very uncommon in estuarine areas but may occasionally float in with the tide. Sand volcanoes covered much of the Settlers Reserve area as a result of the liquefaction caused by the February 2011 Christchurch Earthquake, this is most likely how the marine taxa was introduced.

The western transect at Settlers Reserve had three comparable sites, SRW-Z1, SRW-Z5 and SRW-Z6 while all other zones either have no foraminifera present in either year or only foraminifera present in one year. While sample SRW-Z5 has similar percentages of each foraminifera species present SRW-Z1 and SRW-Z6 do not as both sample sites have shown an increase in the dominance of a single species between 2011 and 2013. Sample site SRW-Z1 shows an increase in *Trochammina inflata* in 2013 and a decrease in *Trochammina salsa* and the introduction of *Haplophragmoides wilberti* while *Jadammina macrescens* disappears completely. Sample site SRW-Z6 shows an increase in the dominance of *Miliammina fusca* and a decrease or disappearance of other most species such as *Ammobaculites exiguus*, *Elphidium advenum*, *Elphidium excavatum*, *Haynesina depressula*, *Entzia macrescens*, *Haplophragmoides wilberti*, *Trochammina inflata* and *Trochammina salsa*.

3.2 Bridge Street Site

The Bridge Street foraminiferal samples were collected along a northern transect and a southern transect as shown in Figure 3.4. This map shows the two transects and the different vegetation zones which samples sites were divided into the same as at Settlers Reserve (See Cochran et al., 2014). There were ten samples collected along each transect (Z+5 – Z5).

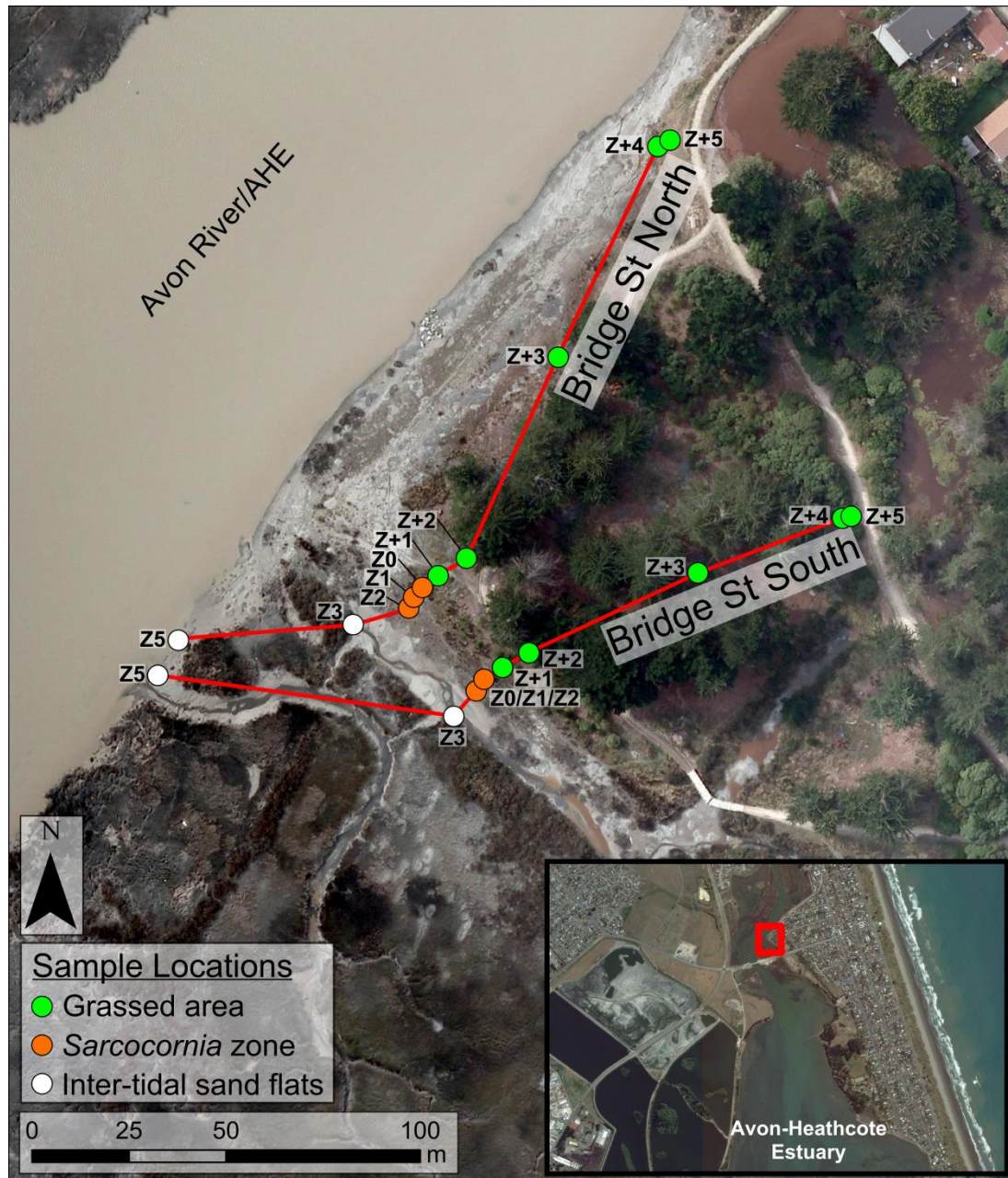


Figure 3.4. Map showing the northern and southern transect lines at the Bridge Street sample site (Adapted from Cochran et al., 2014)

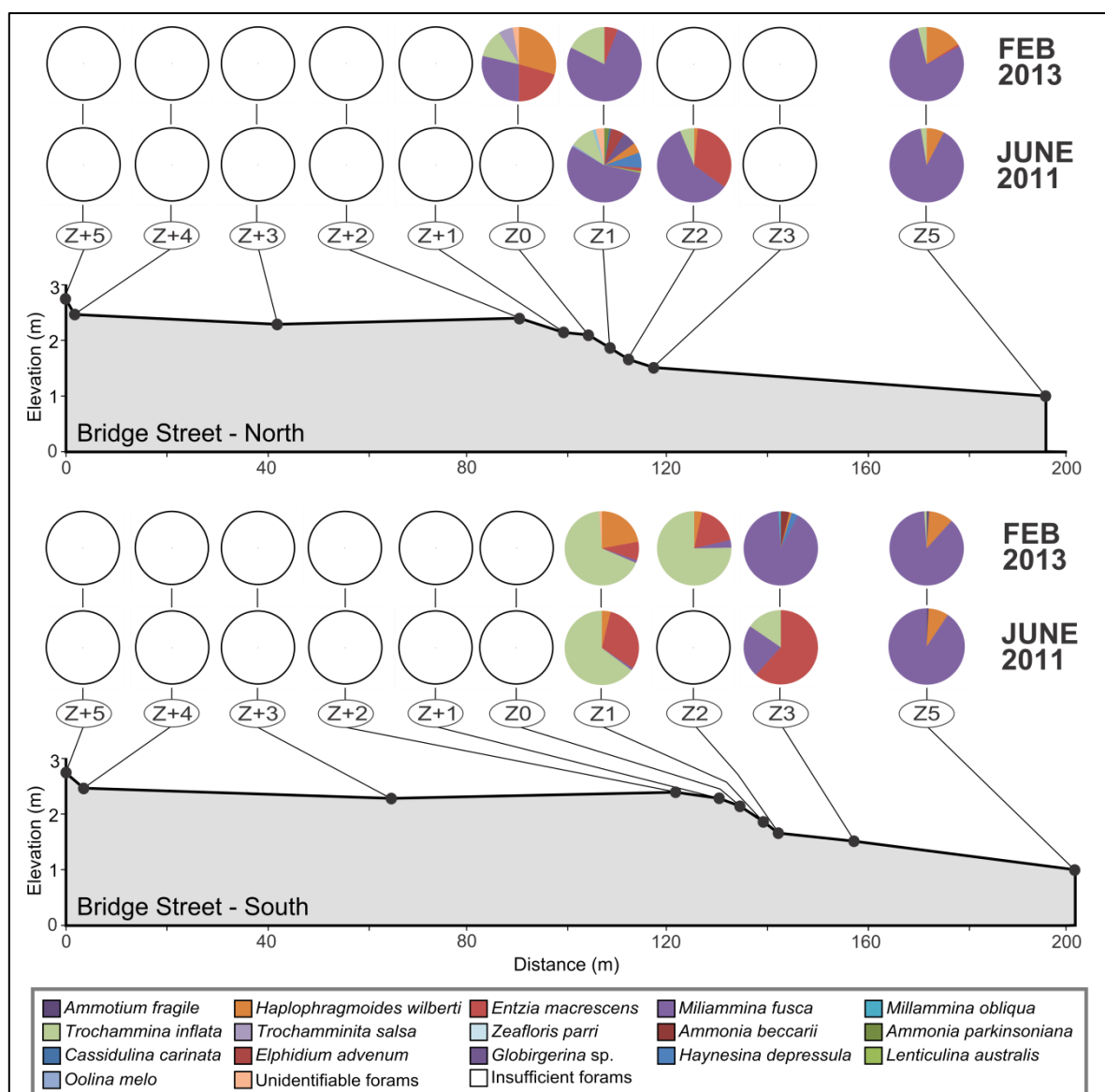


Figure 3.5. Profiles of the northern and southern transects at Bridge Street showing the sample locations. Pie graphs show the normalised species data from June 2011 and February 2013. (Adapted from Cochran et al., 2014)

3.2.1 Foraminifera Changes at Bridge Street

The changes in foraminifera between the June 2011 samples and the February 2013 samples are shown in Figure 3.5 and Appendix A. The pie graphs represent the proportion of each foraminifera species present at the different sampling sites from the June 2011 and the February 2013 samples. Samples with less than one hundred foraminifera tests picked were not included in analysis so not all sites have a sample equivalent for comparison. Bridge Street has undergone coseismic subsidence (Cochran et al. 2014) and intertidal foraminifera could be expected to migrate landward from June 2011 to February 2013.

Only two sample sites were comparable between years along the northern transect at Bridge Street, BSNN-Z1 and BSNN-Z5. Both samples are dominated by the species

Miliammina fusca, while its dominance at BSNN-Z1 increases from 55 % to 76 % its dominance decreases at BSNN-Z5 from 89 % to 79 %. Sample site BSNN-Z1 shows a severe decrease in the number of species present dropping from thirteen in June 2011 to three in February 2013. Key species which are no longer existent at this location are *Elphidium advenum*, *Globergerina* sp, *Haplophragmoides wilberti*, *Haynesina depressula* and *Zeafloris parri*. Sample site BSNN-Z5 does not have such a dramatic change in species present with the only notable difference being the introduction of *Trochammina inflata* (1 %) in February 2013.

Multiple marine taxa were found along the northern transect sample sites in the June 2011 samples. Sample site BSNN-Z1 had, *Cassidulina carinata*, *Globirgerina* sp., *Globorotalia* sp. (BSNN-Z4 sample not pictured) and *Lenticulina australis* present while sample site BSNN-Z4 had *Globorotalia* sp. present. Like at Settlers Reserve it is likely that these species were deposited with the introduced sediments via liquefaction.

There are three sample sites which can be compared along the southern transect at Bridge Street, BSNS-Z1, BSNS-Z3 and BSNS-Z5. Samples taken at BSNS-Z1 and BSNS-Z5 change little between years, sample site BSNS-Z1 increases in percentage of *Haplophragmoides wilberti* from 3.8 % to 22.1 % and decreases in percentage of *Entzia macrescens* from 30.5 % to 8.1 %. Sample site BSNS-Z5 gains one species, *Trochammina inflata*, in February 2013 but it only amounts to 1 % of the total tests present in the sample. Sample BSNS-Z3, however, changes dominant species between the years 2011 and 2013. In June 2011 the dominant species was *E. macrescens* which made up 62 % of the sample while the remainder of the sample was split between *Miliammina fusca* (22 %) and *Trochammina inflata* (15 %). In February 2013 the sample was dominated by *M. fusca* which made up 91 % of all tests in this sample. *T. inflata* is a species which is dominant in high to low salt marshes while *M. fusca* is a species which is dominant along sand flats.

3.3 Species Richness

Species richness was calculated for each sample site at both Settlers Reserve and Bridge Street then averaged along each transect and plotted on Figure 3.6 to be compared between June 2011 and February 2013 (Section 2.6.1). If species richness was not to change along any transect then all transects would plot along the black line as a 1 to 1 ratio. This, however, does not happen and average species richness changes slightly along all transects between June 2011 and February 2013. The Settlers Reserve western transect and the Bridge

Street southern transect both plot slightly below the line indicating that species richness decreased slightly along these transects. The Settlers Reserve eastern transect and the Bridge Street northern transect both plot slightly above the line indicating a slight increase in species richness. A two-tailed one-sample t-test was performed on the change in mean site species richness between 2011 and 2013 and a P-value of 0.865 was generated, as this is above 0.05 it can be said that there is no significant change in species richness between the June 2011 samples and the February 2013 samples.

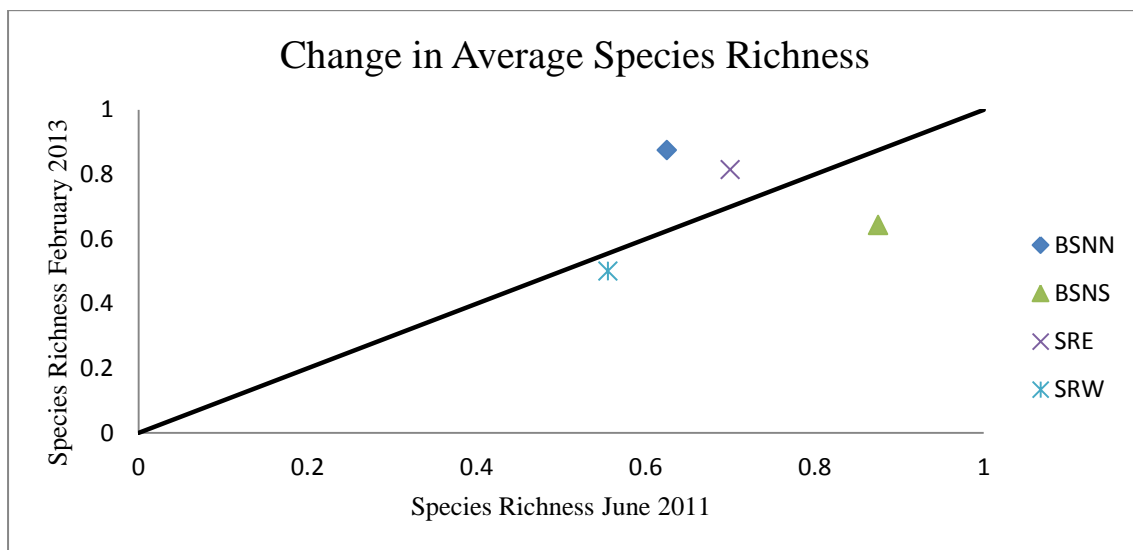


Figure 3.6. Graph showing the change in average species richness at both Settlers Reserve and Bridge Street

3.4 Species Abundance

Change in relative species abundance between June 2011 and February 2013 (Section 2.6.1) was calculated for each of the species present at of the each sample sites at Settlers Reserve and Bridge Street. Only the sample sites which have suitable quantities of foraminifera present as shown in Figures 3.3 and 3.5 are represented in Figure 3.6 and Figure 3.7. In the key each sample site is represented by a symbol then plotted on the graph is a symbol for every species present at each of those sample sites using the sample appropriate symbol. For example each red square represents an individual species which is present at sample site SRW-Z5 and is plotted to show the change in abundance between June 2011 and February 2013.

If every species at every site had the same abundance in 2011 as it did in 2013 then all species would plot along the black line which represents a 1:1 ratio between 2011 and 2013.

This does not happen and while a few species do plot on the line the vast majority do not. Many species are only represented in low percentages causing the clustering at the bottom left corner making it necessary to show Figure 3.8, a zoomed in version of the same graph. While change species abundance does not look close between most June 2011 samples and February 2013 samples only five real outliers exist, two from sample site BSNS-Z3 and one from each of the sample sites BSNS-Z5, SRW-Z1 and SRE-Z5. The Pearson's correlation coefficient was calculated using all species data and a value of 0.73 was found (Section 2.6.1). This represents a strong linear relationship between the samples and species collected in June 2011 and February 2013 thus showing that there has been no significant change in species abundance between the 2 years.

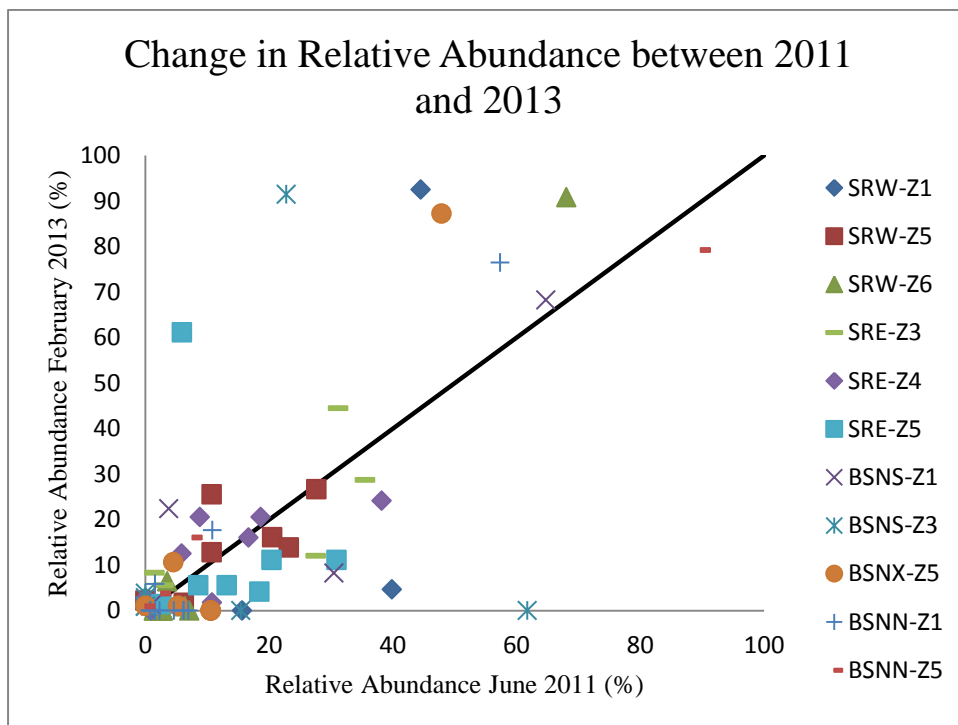


Figure 3.7. Graph showing the change in relative species abundance for each species at each sample site

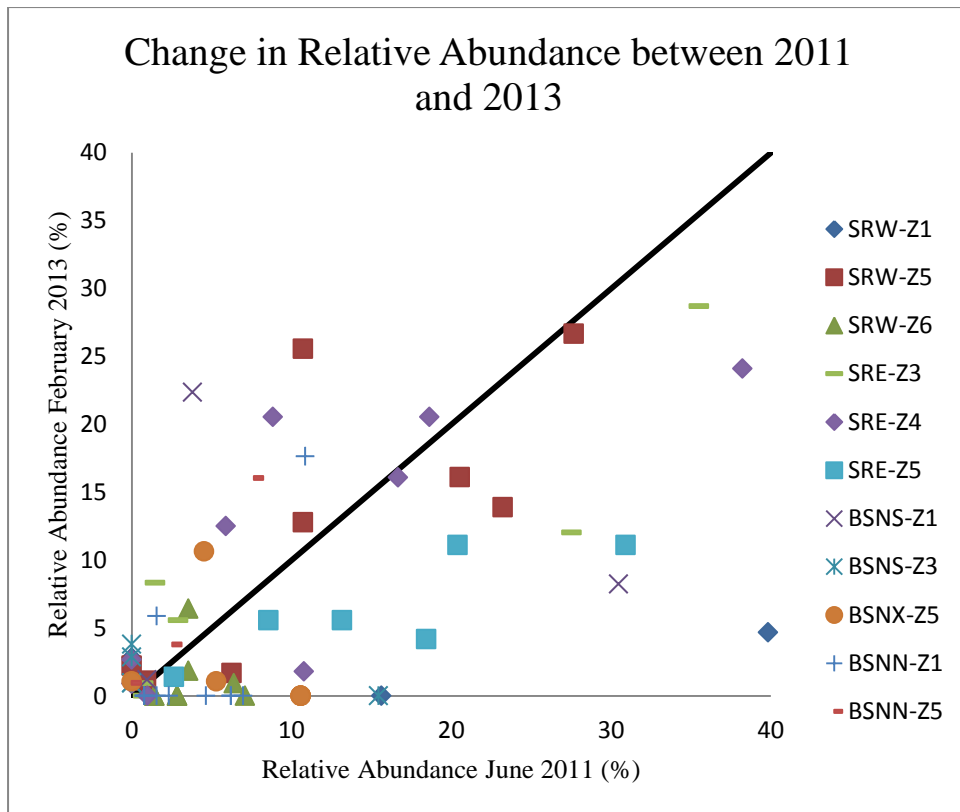


Figure 3.8. The same graph as Figure 3.8 but concentrates on the large cluster

3.5 Summary

The results from chapter three show that there is no clear change in the distribution of foraminifera between June 2011 and February 2013. The expected shift in foraminifera species moving further towards the sea at Settlers Reserve is not seen in any samples although sample SRE-Z5 changes between 2011 and 2013 by increasing the percentage of *Ammobaculites exiguus*. The expected landward shift of foraminifera species at Bridge Street was also not seen although at sample site BSNS-Z3 there is a change in dominant species from *Trochammina inflata* to *Miliammina fusca*. This does indicate that there is some level of landward shift occurring at Bridge Street but it is not significant enough to change the results overall. Marine taxa were introduced to the Avon-Heathcote Estuary in low numbers via liquefaction caused by February 2011 Christchurch Earthquake.

Chapter 4 Transect Results

Chapter 4 includes the results of the data collected along the Settlers Reserve Transect (SRT) in the Avon-Heathcote Estuary as shown in Figure 4.1. This data was collected to establish the present day foraminifera distribution in Settlers Reserve in the AHE.

4.1 Settlers Reserve Transect

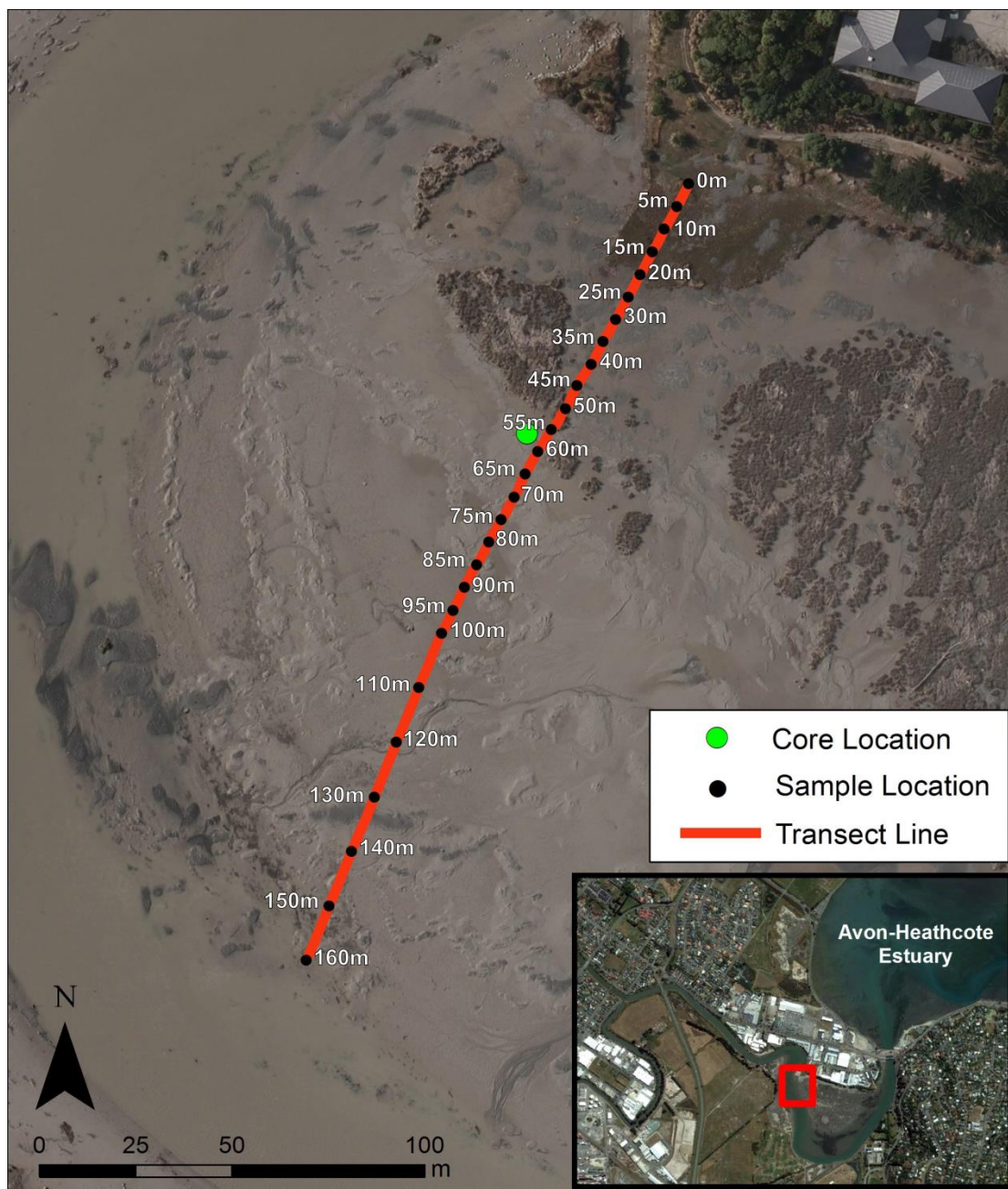


Figure 4.1. Location of the Settlers Reserve field site and the location and direction of the SRT, surface samples and core sampled.

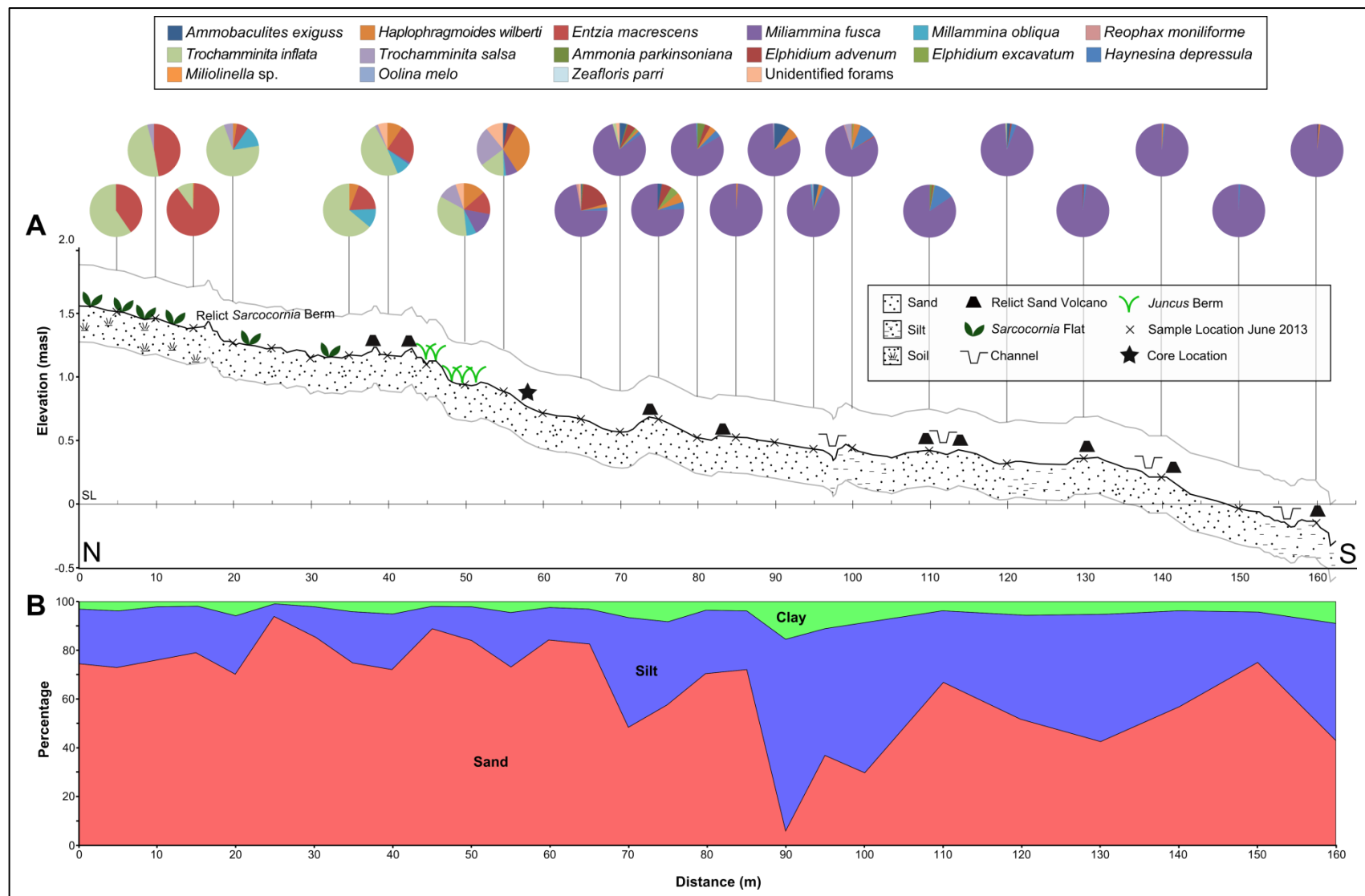


Figure 4.2. A) shows the transect profile with modern salt marsh plant and sand flat distributions and the foraminiferal distribution. B) Sediment data expressed as percentage clay, silt and sand along the transect.

The SRT runs in a straight line following a north-east to south-west trend and is 160 m in length, the methods of collection are described in Chapter 2. The SRT was surveyed and sampled in June 2013, the data collected along the SRT includes foraminifera species, grain size, sediment pH and high tide and low tide salinities. These environmental parameters were compiled to create a detailed model of the location of benthic foraminifera species in Settlers Reserve. These results are then used to show the foraminifera species associations present in Settlers Reserve as well as the environmental conditions controlling the associations.

4.1.1 Transect Morphology

Figure 4.2A shows the SRT tidal height profile is at its most elevated at the most northern end, 1.54 m above sea level. The profile then gradually decreases over the remaining transect to 0.32 m below sea level at the most southern end, a total decrease of 1.86 m in elevation. There are noticeable points along the SRT where estuary morphological features cause height variation, some of which are markers of plant community changes where as others are remnants of sand volcanoes caused by the February 22nd Christchurch earthquake. The X-axis has been exaggerated to show the slight variations in height that occur along the SRT and would otherwise have gone unnoticed.

The general profile is a gradually dipping line from north to south covering 160 m and dropping 1.86 m in elevation. From 0 m to 17 m the transect profile dips gently before the edge of the relict *Sarcocornia* sp., beyond which the profile gradient declines slightly between 18 m and 44 m with only a slight height decrease before raising up with two highly eroded sand volcanoes between 37 m and 44 m. Sand volcanoes have been eroding and spreading out since they were formed in the February 22nd Christchurch Earthquake and there are modified sand volcanoes present along much of the SRT. A *Juncus* berm at 44 m to 52 m marks the beginning of a shallow slope that extends seawards to 70 m. A rise and fall in profile height occurs between 70 m and 80 m where a moderately eroded sand volcano remains, another flatter and further eroded sand volcano is then at 84 m. A gentle decline from 84 m to 97 m is followed by a minor channel with flowing water and steep sides, slightly declining after this until 105 m. Between 105 m and 119 m the profile bears the shape of an elongated mound with a minor channel in the middle and a highly eroded sand volcano either side of the channel. The profile is nearly flat between 119 m and 129 m then rises up slightly due to a highly eroded sand volcano present at 130 m, a moderately steep decline

follows this by ending in a small channel at 138 m. A plateau lies between 138 m and 140 m followed by another highly eroded sand volcano at 141 m, from here the profile declines steeply until 157 m where a minor channel lies. The profile increases slightly between 157 m and 160 m due to a highly eroded sand volcano and then drops down steeply at the end of the profile at 162 m.

The SRT covers a range of tidal heights and zones, with the highest tidal zone lies at the 0 m and the lowest at the 162 m. The majority of the SRT falls within the intertidal zone, the extreme high water spring zone (EHWS) is now at 10 m (following coseismic uplift) and the mean high water spring zone (MHWS) is at 20 m. Mean high water (MHW) straddles the *Juncus* berm and plant zone between 45 m and 55 m while the mean sea level (MSL) is 100 m along the SRT. The 0 m sea level elevation is at 150 m marking the point of mean low water zone (MLW).

The sediment size changes along the SRT as shown in Figure 4.2B, the percentage of sand, silt and clay change relative to one another. Sand is most dominant grainsize across the SRT especially in the first 65 m where sand on average makes up 79.5% of each sample. Silt and clay make up larger percentages of the sediment by 70 m where the slope of the SRT profile decreases. At 90 m there is a large anomaly which does not correspond with the rest of the sediment size results, the percentage of silt increases to 78.3% and clay increases to 15.8%, the highest percentage of either grainsize. This abrupt change in grainsize does not coincide with any noticeable feature along the SRT. Silt and clay continue to be present in higher percentages for the remainder of the SRT, these percentages, however, do not remain constant at any stage.

4.1.2 Transect Plant Communities

The SRT covers a range of plant communities, starting at the northern end of the SRT the old *Sarcocornia* sp. flat lies from the 0 m to 17 m. Due to the uplift that occurred during the Christchurch Earthquake the *Sarcocornia* sp. flat is no longer low lying enough to be covered by EHWS and MHWS and is gradually dying off. The new *Sarcocornia* sp. flat and low salt meadow, now located between 17 m and 40 m, is being progressively populated by *Sarcocornia* sp. in response to the change in tidal height due to the Christchurch Earthquake (Cochran et al. 2014). The *Juncus* berm and salt marsh are located between 45 m and 55 m these have had not noticeably migrated since the Christchurch Earthquake Sequence began, however, they have a broader range than *Sarcocornia* and are less sensitive to tidal height

change (Jones & Marsden, 2005). The rush, *Juncus* sp. is the main component of the *Juncus* berm with the rest composed of tree and plant debris carried down the Heathcote River. Plant species do not grow further than 55 m along the SRT, notably no intertidal or subtidal sea grass flats are present in the Settlers Reserve area of the AHE.

4.1.3 Transect Salinity

Table 4.1. Table showing salinity range in Settlers reserve and global averages

Distance Along Transect	Salinity (Parts per thousand)
High tide	17.4 ppt
Low tide	3.32 ppt

The salinity results show a significant difference between the high tide and low tide salinities, there is a 14.08 ppt difference in salinities. Low tide salinity of 3.32 ppt was recorded at the river end of the SRT whereas 17.4 ppt was recorded at the northern end of the SRT at high tide. Salinity affects the distribution of foraminifera, different species have varying tolerance levels of salinity.

4.1.4 Transect pH

pH values were recorded along the Settlers Reserve transect the tables of data can be seen in Appendix B.

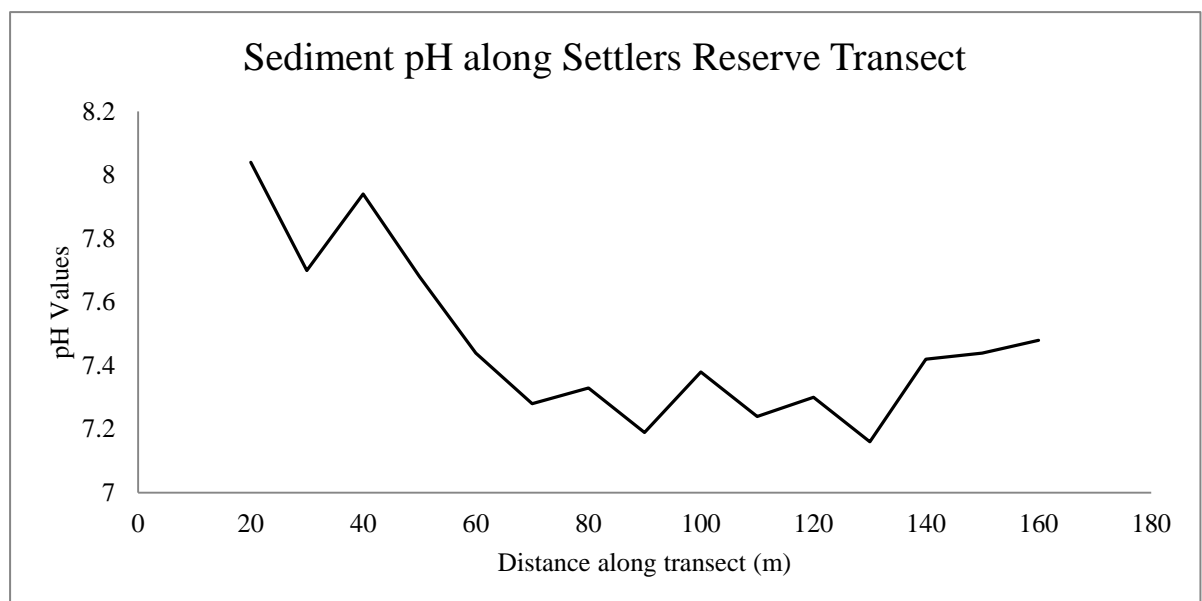


Figure 4.3. Graph showing the pH distribution along the Settlers Reserve Transect

The graph in Figure 4.3 shows a trend with the pH values decreasing down the SRT intertidal profile. The graph shows a sharp drop in pH in the first half of the SRT and plateaus off for the second half while slightly increasing again towards the end. This correlates with the increase in clays and silts along the second half of the SRT. The pH varies by 0.9 from the highest pH of 8.04 to the lowest pH of 7.16, all samples measured are in the range of alkaline pH.

4.1.5 Foraminiferal distribution

The foraminifera species distribution is shown in Figure 4.2A as pie graphs of species found at each sample location. The foraminifera distribution along the SRT is represented by two main groups, agglutinated forms and calcareous forms. Agglutinated foraminifera occur throughout the SRT and represent the highest percentage of tests found at all sample sites along the SRT. All sample locations are dominated by agglutinated foraminifera and with calcareous foraminifera present in small percentages at sample sites between 55 m and 150 m.

The pie graphs show a gradual change in dominant foraminifera species from north to south along the SRT, these species make up large percentages of the total number of foraminifera tests present at each sample location. *Trochammina inflata* and *Entzia macrescens* are the two dominant species present at the higher tidal end of the SRT, *Entzia macrescens* then quickly becomes a minor species after 15 m. *Trochammina inflata* is a dominant species until 50 m where after its prevalence decreases rapidly. *Miliammina fusca* is spread throughout the SRT from 15 m to 160 m although is only dominant at one site, at 55 m where it makes up 37.1 % of the total number of tests present in the sample. *Haplophragmoides wilberti* appears in the highest percentages between 20 m and 100 m then sporadically in low percentages until 160 m. *M. fusca* appears consistently between 40 m and 160 m, although in low numbers between 40 m and 55 m. *M. fusca* becomes the dominant species between 65 m and 160 m representing between 73.2 % and 99 % of all tests present at each of the sample locations.

Less dominant species appear and disappear throughout the SRT, these species make up low percentages of the number of tests present at each site. *Trochamminitq salsa* is the first minor species to occur, it is present in low numbers in half the sample locations between 10 m and 100 m. The maximum amount of *Trochamminita salsa* present in a sample occurs at 55 m where it represents 27.4 % of the total tests found at this sample site. *Miliammina*

obliqua makes a brief appearance between 20 m and 55 m represented in low numbers with the maximum number of tests occurring at 20 m making up just 12.8 % of the total number of tests present in this sample location. *M. obliqua* makes two more minor appearances between 80 m and 95 m although never making up more than 1 % of the total tests present in a sample. *Ammotium fragile*, *Ammobaculites exiguus* and *Reophax moniliforme* are the three species of agglutinated foraminifera which have the lowest percentages of tests present throughout the SRT. *Ammotium fragile* is only present at 160 m and represents 1 % of total tests at this site. *R. moniliforme* is only present in two sample locations, 65 m and 100 m, making up 1.5 % and 0.7 % of the tests located at each site respectively. *Ammobaculites exiguus* is present at seven sites between 55 m and 120 m and makes up between 0.7 % and 9.7 % of the tests present at each site, *Ammobaculites exiguus* is most abundant at 90 m.

There are 5 species of calcareous foraminifera found between 55 m and 150 m, all calcareous foraminifera represent low percentages of the total tests found at each sample location they appear in. *Haynesina depressula* and *Elphidium advenum* are present at the most sample locations and have the most tests present along the SRT out of all the calcareous foraminifera. *H. depressula* is present at sample sites between 65 m and 150 m and is most abundant at 100 m and 110 m being 10.4 % and 12.4 % of the tests present at each of the sample sites respectively. For the remainder of the samples that *H. depressula* is present in the percentage of tests present ranges from 1.03 % to 4.3 %. *E. advenum* is present at sample sites between 55 m and 130 m and is most abundant at 65 m where *E. advenum* makes up 19.6 % of the total tests present at this site. For the remainder of the sample sites which *E. advenum* is present at the percentage of tests present ranges from 0.8 % to 6.1 %. *Ammonia parkinsoniana*, *Buccella frigida* and *Elphidium excavatum* are 3 species of calcareous foraminifera which are found in even lower percentages along the SRT than the previous two mentioned species. *Ammonia parkinsoniana* is present in low numbers between 65 m and 110 m with the highest percentage of this species present at 80 m where it represents 4.8 % of the tests present at this sample site. The three other sites where *Ammonia parkinsoniana* is located the percentages this species makes up of the tests present ranges from 0.7 % to 1.6 %. *B. frigida* is only present at the 100 m sample site and makes up 0.7 % of the sample. *E. excavatum* is present in samples between 70 m and 110 m with the highest percentage of this species present at 75 m where it represents 5.2 % of the tests present at this sample site. The three other sites where *E. excavatum* is located the percentages this species makes up of the tests present ranges from 0.7 % to 1.5 %.

4.1.6 Diversity of Foraminifera along the Settlers Reserve Transect

The diversity indices are calculated to better define the foraminiferal distribution of the Settlers Reserve Transect. Diversity of the individual samples along the SRT is determined using the number of species present, Shannon – Wiener information function (Shannon_H), Fisher alpha index and Evenness from which we can determine the overall diversity of the Settlers Reserve area of the AHE.

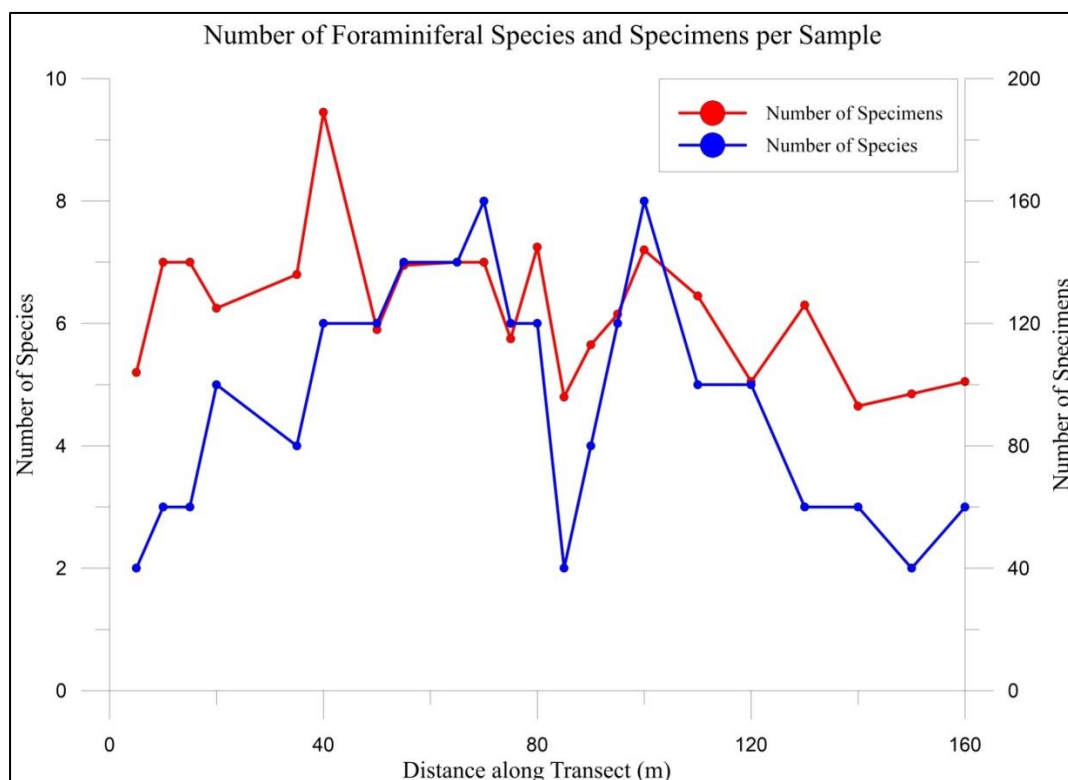


Figure 4.4. The number of species per sample and number of specimens per sample along the SRT.

Figure 4.4 shows the number of species per sample along the SRT coupled with the number of specimens, the general trend is a bell curve with an anomaly occurring at 85 m. The number of species per sample gradually increases over the first half of the SRT and then gradually decreases over the second half of the SRT. The maximum number of species per sample is eight occurring at both 70 m and 100 m while the minimum number of species per sample is two occurring at three locations, 5 m, 85 m and 150 m. The sharp decrease in species numbers at 85 m coincides with the edge of a sand volcano although the same thing occurs at many other sample locations and this does not appear to have an effect on the

number of species present at the other sample locations. No other noticeable change occurs on the SRT at this sample location and this stage will be seen as an anomaly.

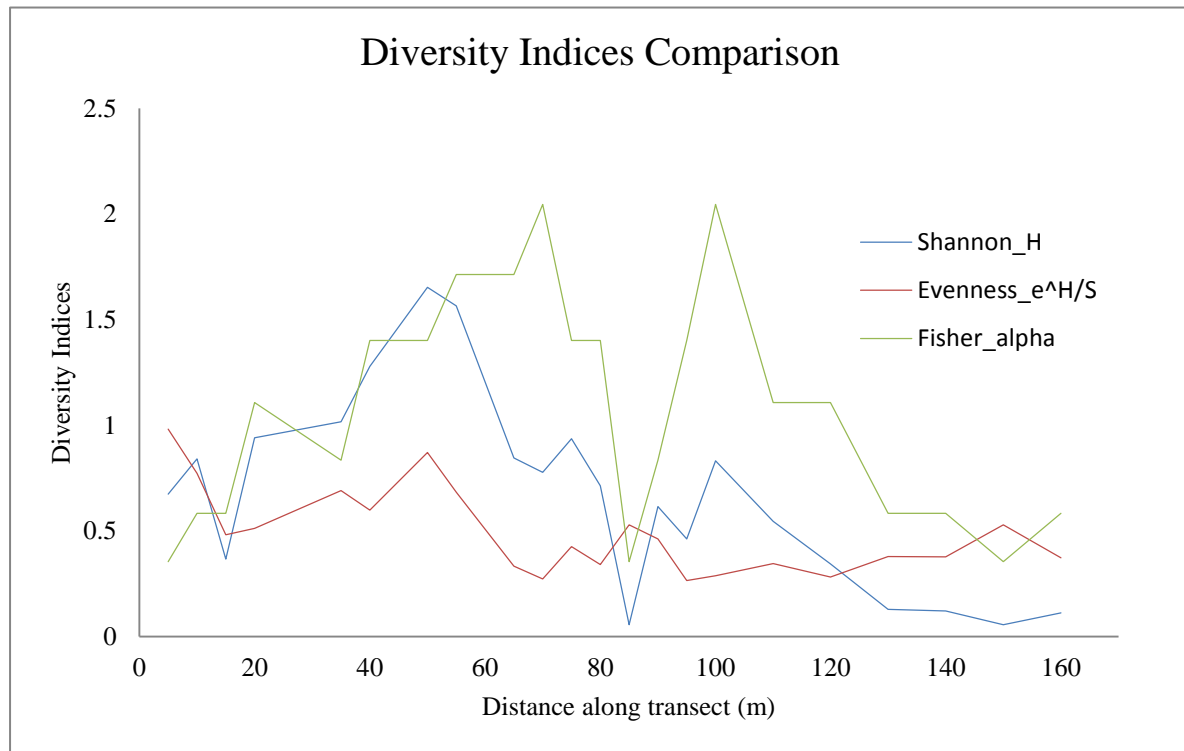


Figure 4.5. Diversity indices per sample along the SRT

Figure 4.5 shows the diversity indices used in this study. The Shannon – Weiner information function (SH) ($H_{(S)} = - \sum P_i \log_e P_i$) does not put much emphasis on the rarer or very abundant species but takes into account the Evenness of species counts and the number of species present. The maximum index for the SH is 1.65 which occurs at 50 m, this coincides with the second highest Evenness measurement, because Evenness is one of the major influences on the SH this is not surprising. The minimum index of the SH is 0.056 which occurs at both 85 m and 150 m this coincides with the samples with the lowest numbers of species present. The SH increases over the first 50 m of the SRT then decreases, with some variation, over the last 110 m, when comparing this to the pie graphs shown in Figure 4.2A it follows the same trend. As the number of species present increases on the pie graphs the SH increases, when the pie graphs change at 65 m and the species are dominated by *Miliammina fusca*, the SH begins to decline. *M. fusca* becomes more dominant towards the end of the SRT and very abundant species do not have much emphasis placed on them in this calculation so this coincides with the declining SH trend. The number of species present declines after 100 m and this coincides with the near constant decrease in the SH after 100 m. The SH shows the same anomaly as Figure 4.4 at 85 m where a sharp decrease is seen, this is

because the SH is influenced by the number of species present and the sudden decrease in species present equates to a decrease in diversity.

Evenness ($E = e^H/S$) measures how even the species counts for each sample are no matter how many species are present and Evenness is measured out of 1. Evenness does not follow a general trend throughout the SRT, although it is highest over the first 50 m and then drops below 0.5 for the remainder of the SRT with only two exceptions at 85 m and 150 m respectively. The sample location with the highest measured Evenness is 5 m measured at 0.98, only 2 species are present in this sample, the second highest measured Evenness is at 50 m measured at 0.87 with 6 species present in the sample. The sample locations with the lowest measured Evenness are 70 m, 95 m, 100 m and 120 m, these samples are hardly distinguishable with measurements of 0.27, 0.26, 0.29 and 0.28 respectively. These samples all have between six and eight species present although all samples are dominated by high percentages of *M. fusca* which drags down the Evenness of the samples. Evenness is the only diversity measurement which increases at both 85 m and 150 m all others decrease compared to the samples on either side of it. This could be because there are only two species present at both locations.

The Fisher alpha index (α) ($\alpha = N(1 - \chi) / \chi$) taking into account the number individual tests and the number of species present. The α follows closely the same trend as the number of species seen in Figure 4.4, as the number of species increases over the first half of the SRT the α increases, as the number of species decreases over the second half of the SRT so does the FAI. The maximum value for the α is 2.05 which occurs at two locations, 70 m and 100 m, at both these locations the number of species present is eight which is the highest of all samples. The minimum value for the α is 0.35 which occurs at three locations, 5 m, 85 m and 150 m, at all of these locations the number of species present is two which is the lowest of all samples. At the 85 m sample location the α sharply decreases mimicking the graph in Figure 4.4, again this is because the number of species present strongly influences the α .

4.1.7 Key Foraminifera Species

The four most dominant foraminifera species found along the STR are shown in Figure 4.6. *Trochammina inflata* and *Entzia macrescens* are both live within the salt meadow and they are the dominant species the first 50 m of the SRT. *Haplophragmoides* lives in the salt marsh around the *Juncus* berm and it is the dominant species at 55 m along the SRT.

Miliammina fusca is the most dominant of all the species present along the SRT, it lives on the intertidal sand flats and is the dominant species from 65 m to the end of the transect at 160 m.

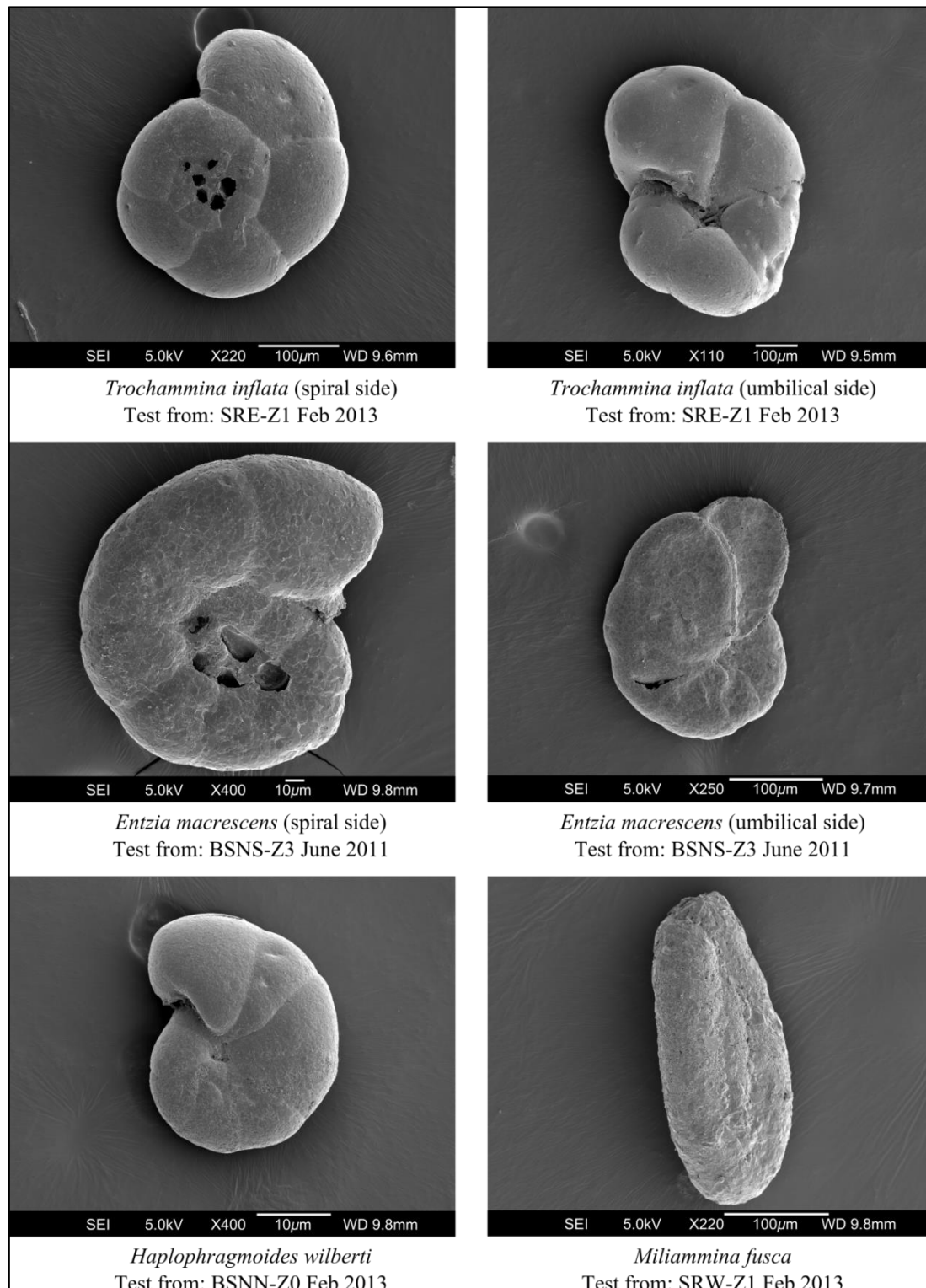


Figure 4.6. The foraminifera species present in the highest percentages along the SRT (SEM Kerry Swanson)

4.2 Foraminifera Associations

4.2.1 Cluster analysis

Foraminiferal associations were established along the Settlers Reserve Transect using Bray-Curtis cluster analysis and dendrogram classifications (Figure 4.7) as described in Section 2.6.2. Foraminiferal associations of the SRT are separated into sample associations (X-axis) and species associations (Y-axis), samples cluster together influenced by the species present within the samples, particularly the dominant species. Species cluster together influenced by what species occur most commonly together and can only appear in one species association. Along the X-axis there are two strong species associations, the *Trochammina inflata* association is between 5 m and 50 m and the *Miliammina fusca* association between 60 m and 160 m. Two minor species associations are located at 15 m and 55 m; the *Haplophragmoides wilberti* sample association and the *Entzia macrescens* sample association. The Y-axis is divided into three species associations, these are labelled by numbers, 1, 2 and 3 and are not always grouped by the most dominant species.

4.2.1.1 Sample Associations

E –*Entzia macrescens*:

Habitat: *Sarcocornia*, low salt meadow

Tidal level or depth: EHWS

Sediment: Slightly silty medium sand

Diversity: Very low; SH = 0.37 – 0.84 (mean 0.63), E = 0.48 – 0.98 (mean 0.75), α = 0.35 – 0.58 (mean 0.5)

Fauna: This sample association is dominated by *Entzia macrescens* (mean 68 %) with common secondary species *Trochammina inflata* (mean 29.3 %), *Trochammina salsa* (4.3 %)

Ecological distribution: The *Entzia macrescens* sample association occurs around EHWS level with salinity levels around 17.4 ppt in a low salt meadows and *Sarcocornia* flats

Transect Location: 15 m

Tn – *Trochammina inflata*

Habitat: *Sarcocornia* sp. flat, Low salt meadow

Tidal level or depth: EHWS to MHWS

Sediment: Slightly silty medium sand

Diversity: Very low to low; SH = 0.67 – 1.65 (mean 1.06), E = 0.51 – 0.98 (mean 0.74), α = 0.35 – 1.4 (mean 0.95)

Fauna: This association is dominated by *Trochammina inflata* (mean 55.4 %), with common secondary species *Entzia macrescens* (mean 25.6 %), *Trochammina salsa* (mean 6 %), *Haplophragmoides wilberti* (mean 5.8 %), *Miliammina oblique* (mean 10 %)

Ecological distribution: This association occurs around EHWS to MHWS with salinity levels of around 17.4 ppt and mean pH levels 7.84, in a low salt meadow and *Sarcocornia* sp. flat.

Transect Location: 5 m – 10 m, 20 m – 50 m

H – *Haplophragmoides wilberti*:

Habitat: *Juncus* berm, salt marsh

Tidal level or depth: MHW

Sediment: Silty medium sand

Diversity: Low, SH = 1.6, E = 0.68, F α = 1.7

Fauna: This association is dominated by *Haplophragmoides wilberti* (37.1 %), with common secondary species *Trochammina salsa* (27.1 %), *Trochammina inflata* (16.9 %), *Miliammina fusca* (8.1 %), *Elphidium advenum* (5.6 %), *Ammobaculites exiguus* (3.2 %), *Miliammina obliqua* (1.6 %)

Ecological distribution: This association occurs around MHW tidal depth with a mean sediment pH of 7.56, in a salt marsh at the *Juncus* berm

Transect Location: 55 m

M – *Miliammina fusca*:

Habitat: Sand flat

Tidal level or depth: MHW – MLW

Sediment: Sandy silt – silty medium sand

Diversity: Very Low – Low, H = 0.056 – 0.94 (mean 0.47), E = 0.26 – 0.53 (mean 0.37), α = 0.35 – 2.05 (mean 1.1)

Fauna: This association is dominated by *Miliammina fusca* (mean 88.1 %), with common secondary species *Haplophragmoides wilberti* (mean 3.1 %), *Elphidium advenum* (mean 5.3 %), *Haynesina depressula* (mean 4.1 %), *Ammobaculites exiguus* (mean 3.8%), *Elphidium excavatum* (mean 2 %), *Ammonia parkinsoniana* (mean 2 %)

Ecological distribution: This association occurs around the MHW to MLW tidal depth, on a sand flat, with salinity around 3.32 ppt and a mean sediment pH of 7.3.

Transect Location: 60 m – 160 m



Figure 4.7. Dendrogram classifications of the benthic foraminifera sample associations present along the Settlers Reserve Transect produced by cluster analysis using Bray-Curtis distance and species associations. M = *Miliammina fusca* association, H = *Haplophragmoides wilberti* association, Tn = *Trochammina inflata* association and E = *Entzia macrescens* association. The Y-axis species are not grouped or coloured into traditional species associations.

4.2.1.2 Species Associations

Species can only appear in one species association per dendrogram classification and this is determined by the species which they appear most commonly with. The dominant species in species associations can differ from those which appear in the sample associations.

Species Association 1:

Fauna: Species association 1 is made up of a single agglutinated species, *Ammotium fragile*.

Sediment: Sandy silt

Distribution: Species association 1 is only located at 160 m and makes up only 1 % of the species present in the sample.

Species Association 2:

Fauna: Species association 2 has no dominant species, there are five species which all appear in low quantities along the SRT, four calcareous species *Elphidium advenum*, *Haynesina depressula*, *Elphidium excavatum* and *Ammonia parkinsoniana* and one agglutinated species and *Ammobaculites exiguus*.

Sediment: Sandy silt – silty medium sand

Distribution: Species association 2 is distributed between 55 m – 160 m, *H. depressula* is the most prominent species in this association appearing at all but three locations along this segment of the transect. *Ammobaculites exiguus*, *E. advenum*, *E. excavatum* and *Ammonia parkinsoniana* are all more prominent in the first half of this segment of the SRT occurring between 55 m – 120 m. *Ammotium fragile* only occurs once along this segment at 160 m, it is the only species in this association to appear at this location.

Species Association 3:

Fauna: Species association 3 has three dominant species and two secondary species, all are agglutinated. *Haplophragmoides wilberti*, *Entzia macrescens* and *Trochammina inflata* are the dominant species in this association and *Miliammina oblique* and *Trochamminita salsa* are the secondary species.

Sediment: Slightly silty – silty medium sand

Distribution: Species association 3 is distributed between 5 m – 160 m, *H. wilberti* has the widest range in this association from 15 m to 160 m but is most dominant at 55 m. *E. macrescens* is prominent mainly between 5 m and 50 m although makes an appearance at 100 m, it is most dominant at 15 m. *Trochammina inflata* is prominent between 5 m and 55 m although appears again at 70 m, it is most dominant between 5 m and 50 m. *M. oblique* and

Trochammina salsa are distributed between 10 m and 100 m, these species represent a low percentage of overall species present.

Species Association 4

Fauna: Species association 4 has one dominant species, *Miliammina fusca*, which is agglutinated and two secondary species *Buccella frigida* and *Reophax moniliforme*, calcareous and agglutinated respectively.

Sediment: Sandy silt – silty medium sand

Distribution: Species association 4 is distributed between 40 m and 160 m, *M. fusca* has the widest range in this association from 40 m to 160 m but is most dominant between 65 m and 160 m. *Buccella frigida* and *Reophax moniliforme* are very minor species only appearing in low percentages at 100 m and 65 m between them.

4.2.2 Detrended Correspondence Analysis

The Detrended Correspondence Analysis shown in Figure 4.8 analysis uses a 4 axis plot to arrange the samples according to their closest associations taking into consideration different environmental parameters. Each axis represents a different environmental parameter, for example, tidal height, salinity, sediment size or pH, the Eigenval value shown defines how strong the correlation of each axis is with 1 being strongly correlated and 0 being not correlated. The Eigenval values shown in Figure 4.8 show the first axis with a strong Eigenval value of 0.9052 all other axis have a Eigenval value below 0.1 and are not found to correlate with any of the environmental parameters measured. Axis one correlates strongly with tidal height, where samples on the far right are found at the highest tide and the samples on the left are found at the lowest tidal height.

Entzia macrescens sample association (green), is correlated with tidal heights. The sample was collected from an old *Sarcocornia* flat which is in a low salt meadow. The *Entzia macrescens* sample association appears to be very specialised only appearing in one location although the species *Entzia macrescens* also appears in high percentages in both the 5 m and 10 m samples which accounts for why they are grouped so closely.

Trochammina inflata is the sample association (brown), it is shown to be found in a similar environment to *Entzia macrescens*. This sample association is common at high tidal levels, both the old and new *Sarcocornia* flats as well as a low salt meadow. The *Trochammina inflata* species association is more wide spread than the *E. macrescens* species association and is present on either side the *E. macrescens*. *Miliammina oblique* and

Trochamminita salsa are grouped with this association which is synonymous with the description of the *Trochammina inflata* species sample in Section 4.2.1.1.

Haplophragmoides wilberti sample association (red), it is shown to be driven by being located in the MHW zone, the *Juncus* berm and on a salt marsh. This association groups both the 50 m and 55 m samples into it which is different to what is shown in Figure 4.7 which only incorporates the sample at 55 m into the *Haplophragmoides wilberti* association. Looking at the pie graphs shown in Figure 4.2A the *Haplophragmoides wilberti* is only dominant at 55 m while the sample at 50 m is dominated by *Trochammina inflata*, these associations are close together and share many of the same minor species which is why the sample at 50 m appears to be interchangeable.

Miliammina fusca sample association (orange), it is shown to be driven by low tidal heights and being spread over sand flats in the intertidal zone. This association is the most wide spread covering nearly two thirds of the SRT, there are many minor species as mentioned in Section 4.2.1.1 of both the calcareous and agglutinated varieties. This sample association is not grouped as closely along Axis 1 as the other species associations showing that its environmental parameters are quite different including many different minor species, lower tidal heights and no plant cover.

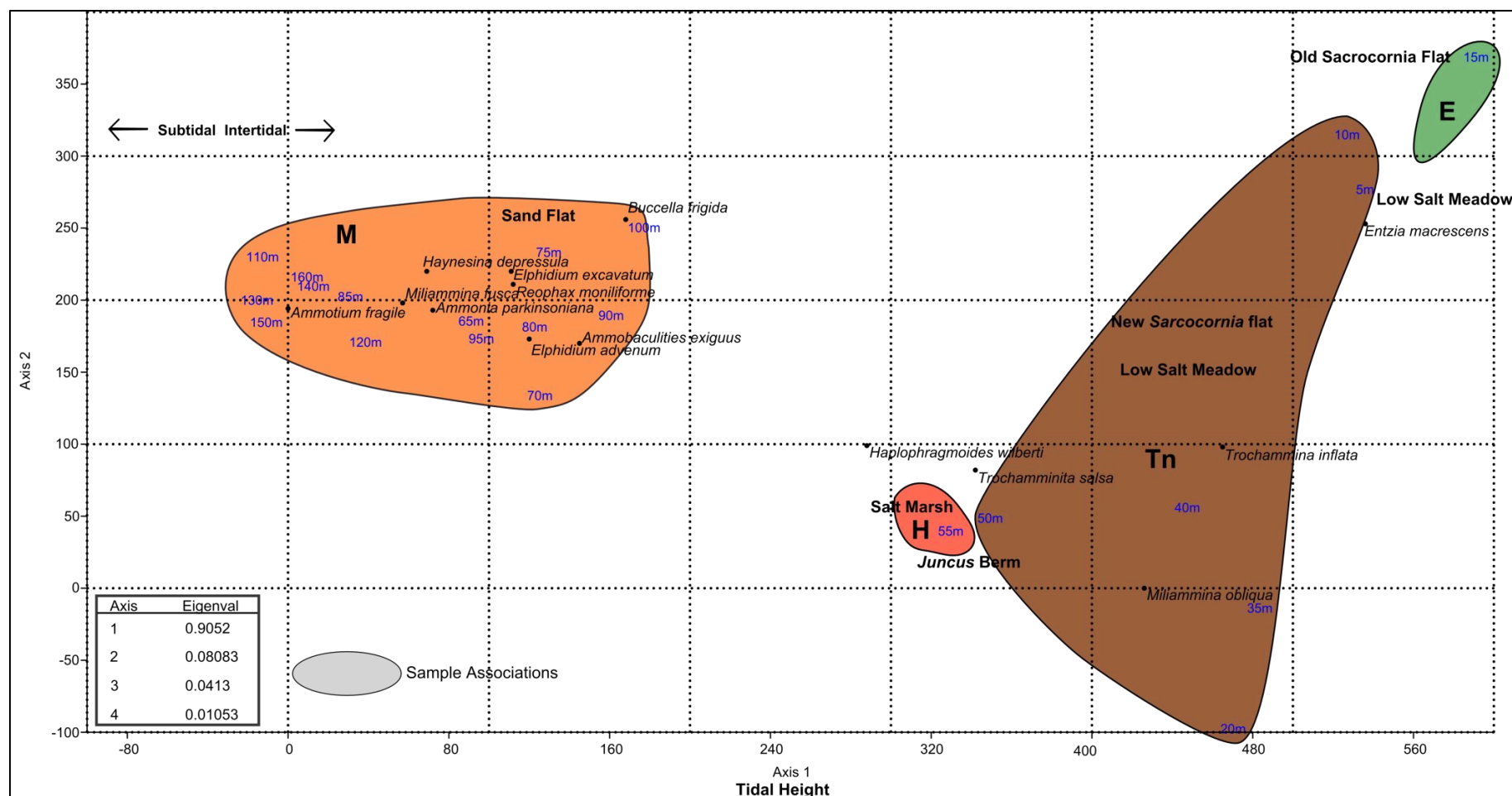


Figure 4.8. A two dimensional configuration of the foraminifera species and samples along the Settlers Reserve Transect produced by Detrended Correspondence Analysis. The axes group the samples and foraminifera species together by shared environmental factors. The Eigenval value for Axis 2 is extremely low so there is no significant environmental association of species and sample distribution in the Y axis. The Eigenval value for Axis 1 is, however, shows a very strong environmental association of species and sample distribution with tidal height. The species association codes are M = *Miliammina fusca*, Tn = *Trochammina inflata*, E = *Entzia macrescens*, H = *Haplophragmoides wilberti*. The environmental associations present are tidal height, the old *Sacrocornia* flat, the *Juncus* berm, low salt meadow, salt marsh and sand flats.

4.3 Summary

Chapter 4 describes the distribution of foraminiferal species along a 160 m transect collected in the Avon-Heathcote Estuary at Settlers Reserve. The species distribution changes along the SRT coinciding with changes in tidal zonation and vegetation, with high tide species *Trochammina inflata* and *Entzia macrescens* at the northern end of the transect and mid to low water species *Haplophragmoides wilberti* and *Miliammina fusca* at the southern end. There is low overall species diversity at Settlers Reserve with only four dominant species and ten minor species in the area. The transect profile still shows the effects of coseismic deformation from the 2011 Christchurch Earthquake on the Estuary with eroded sand volcanoes still visible.

Chapter 5 Core Results

This chapter contains the results for the Settlers Reserve Core (SRC) collected in the Avon-Heathcote Estuary. The core location is shown in Figure 5.1, taken 57 m along the Settlers Reserve Transect (SRT). The core was analysed to determine the development of the AHE and potentially identify and historic coseismic deformation. The results presented include, grainsize, foraminifera present, trace metal analysis and carbon and nitrogen isotopes. Grainsize and foraminifera results are presented to determine past environments of the AHE and possible historic coseismic deformation. Trace elements and total organic carbon results are presented to assist with developing an age profile for the core using information about the arrival of Europeans and the timing of different industries to help restrict the age range.

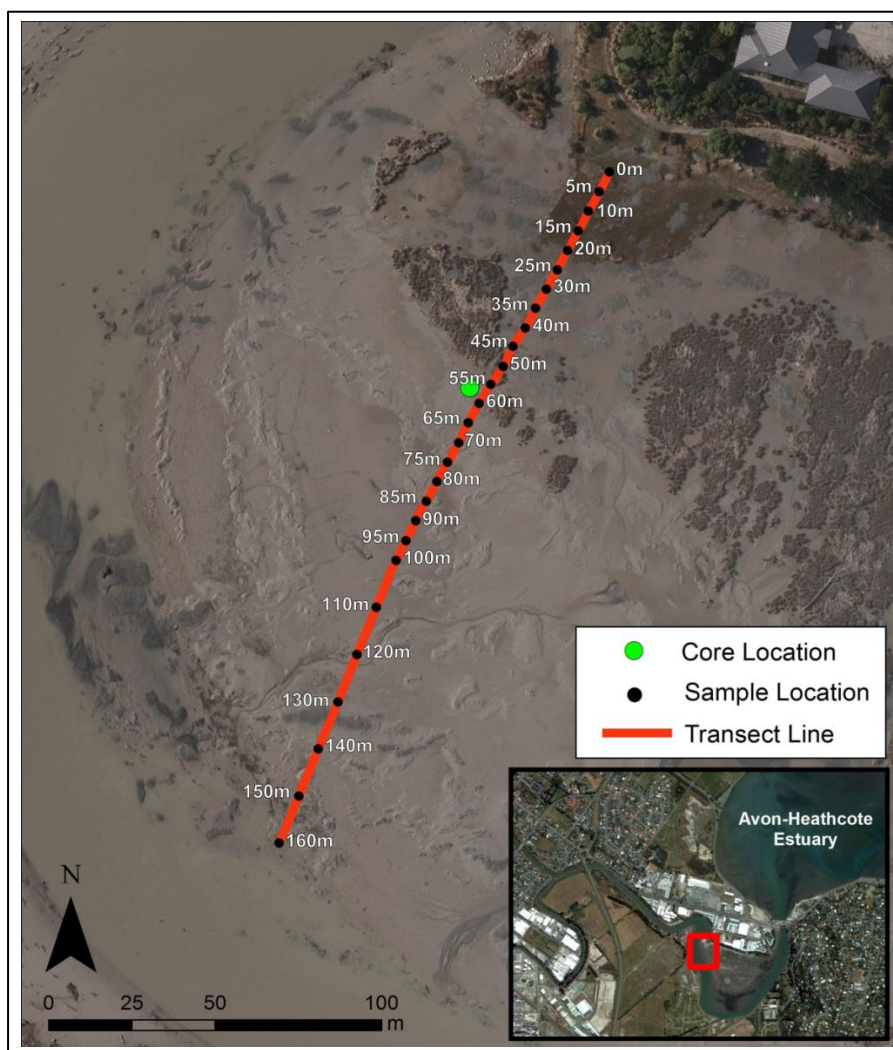


Figure 5.1. Location of the core taken in Settlers Reserve

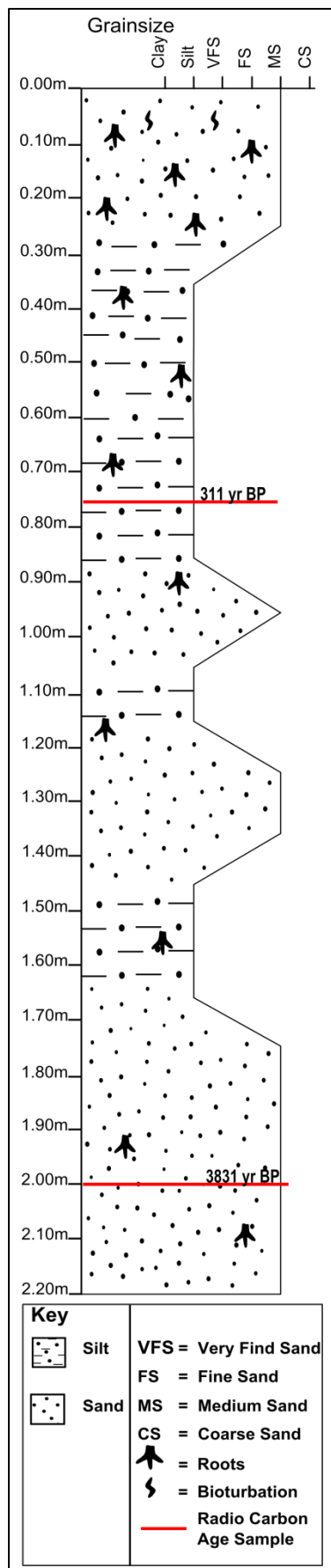


Figure 5.2. General core log showing grainsize and the locations of radio carbon dated samples

5.1 Core Log

The SRC is 2.20 m in length, this is the depth which coring was possible to with a hand corer and the entire core was recovered. The core is described as follows:

From 0 m to 0.03 m the core is dark grey bioturbated medium sand, the sand is damp and crumbles. There is a sharp boundary at 0.03m where the core changes to dark brown to black silty medium sand with some clay, this is firmly held together sediment which is organic rich with a lot of plant roots binding it together and is heavily bioturbated. From 0.25 m the core grades over 10 cm into a dark grey sandy clayey silt which is still firmly held together and has a few rootlets throughout it, there are darker patches containing organic rich material. There is no change in the core until 0.75 m where there is a defined organic layer, which is covered in plant material which is horizontal in orientation and *in-situ*. After 0.75 m the core continues with the same silt description as prior to the organic layer. From 0.85 m the core grades over 10 cm into a dark grey silty medium sand which is firm to touch and contains a few rootlets. The core then grades straight back into a dark grey sandy clayey silt over 10 cm from 0.95 m, which contains only one rootlet. From 1.15 m the core grades over 10 cm into dark grey silty medium sand which is firmly held together and has some rootlets. From 1.35 m the core grades over 10 cm into a medium grey sandy clayey silt with a few rootlets and is firmly held together which continues until 1.65 m. Between 1.65 m and 1.75 m the core grades into a medium grey silty medium sand with a few rootlets, the sand is damp and crumbly. Between 2.07 m and 2.13 m the sand changes and becomes very watery and slushy and then returns to crumbly medium grey silty medium sand

with rootlets.

The ages of two samples from the core were analysed using Radiocarbon (RC) dating as outlined in Section 2.3.3 and in Appendix C. The organic material was taken from the sandy silt at 0.75 m and dated at 311 years before present (y.b.p.) (2013). The bulk sediment sample taken from the silty sand at 2.0 m was dated at 3831 y.b.p. (2013). The validity of these ages will be discussed further in Chapter 6.

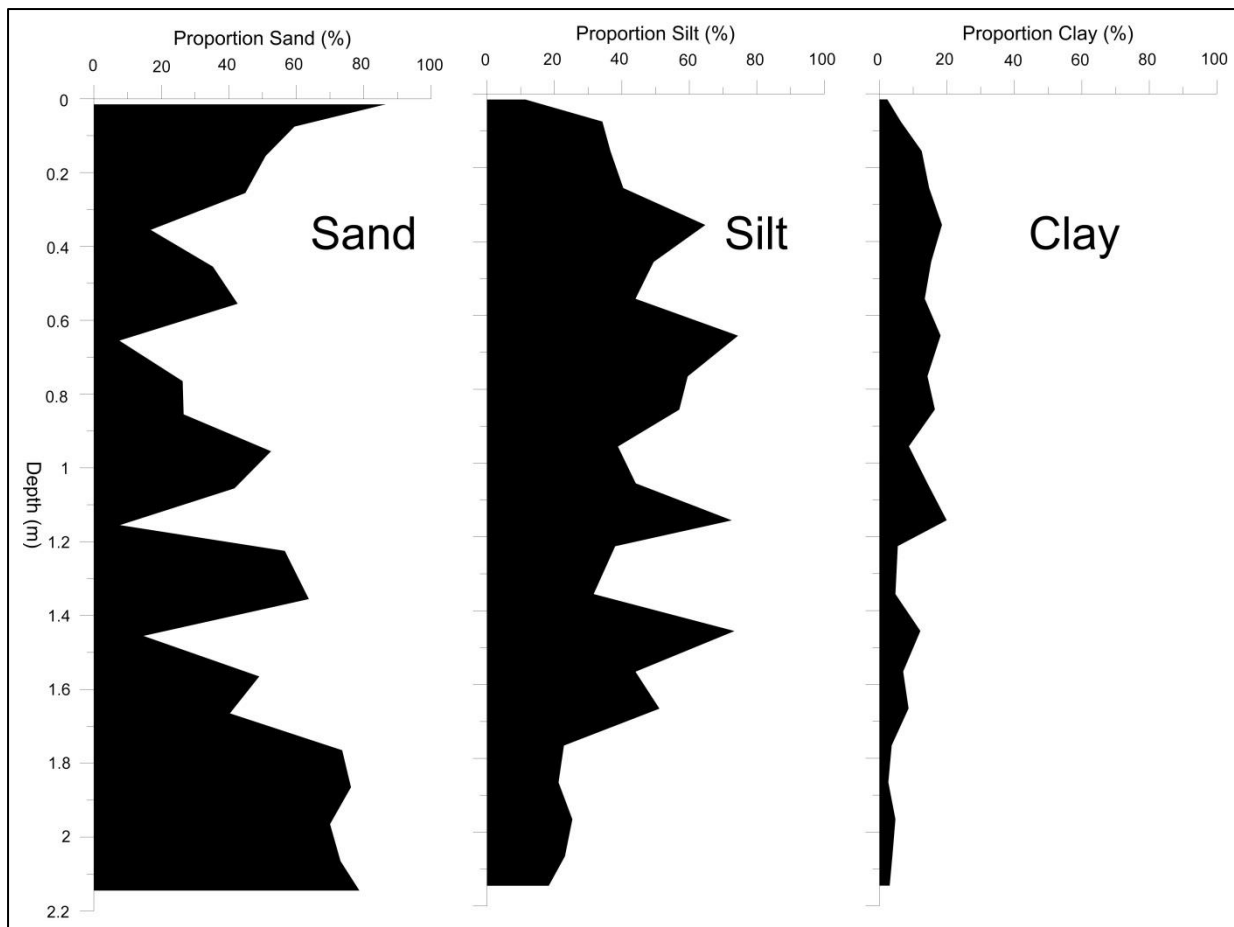


Figure 5.3. Percentage of Sand Silt and Clay down the SRC.

The percentages of sand, silt and clay vary throughout the core with sand being more dominant at the top and bottom of the core while silt was more prominent in the middle (Figure 5.3). Clay only makes up a small percentage of the sediment throughout the core, on average 10 %, although it does appear in higher percentages at 1.15 m with 20 %.

5.2 Results of Foraminiferal Analysis

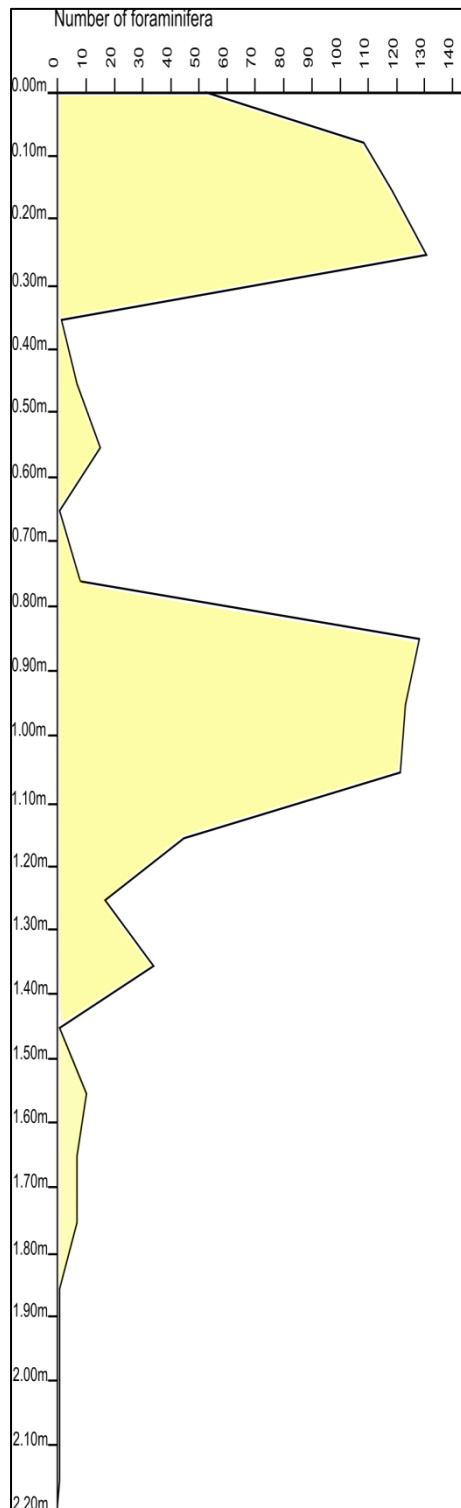


Figure 5.4. The distribution of the number of foraminifera in the Settlers Reserve Core (non-normalised). The X-axis shows the total number of foraminifera found at each sample location and the Y-axis shows the distance down the core.

5.2.1 Number of Foraminifera

Foraminifera are not distributed evenly down the core with large gaps in abundance (Figure 5.4). Foraminifera are most abundant in the top half of the core while the bottom half has very few tests present. Between 0 m and 0.35 m there are reasonable numbers of foraminifera present with the highest number found at a depth of 0.25 m with 131 tests found, between 0.35 m and 0.75 m there are very few foraminifera with the most present at 0.55 m with 15 tests. Between 0.75 m and 1.15 m the amount of foraminifera found increases again with the largest number found at 0.85 m with 128 tests present. Below 1.15 m the number of foraminifera present never recovers. There is a small peak at 1.35 m where there were 34 tests found but below this significant numbers of foraminifera are not present with only between 0 and 10 tests found in each sample.

In the top 1.35 m of core the high abundance of foraminifera can be loosely correlated with a section of core with high percentages of sand, however, lower in the core there is not clear correlation between grainsize and foraminifera abundance (Figure 5.3 and Figure 5.4)

5.2.2 Foraminifera Species Present

The foraminifera species present in the Settlers Reserve Core change progressively down the core. Nine species are present within the core, these have predominantly agglutinated tests with only two

calcareous species found, one calcareous species was found in the surface sample while the other was found further down in the core at 1.35 m. The species present in the core are presented in Figure 5.5, *Haplophragmoides wilberti*, *Miliammina fusca* and *Trochammina inflata* are the three main species present in the core with lower occurrences of *Trochammina salsa*, *Entzia macrescens*, *Ammotium fragile*, *Reophax moniliforme*, *Elphidium advenum* and *Globorotalia* sp.

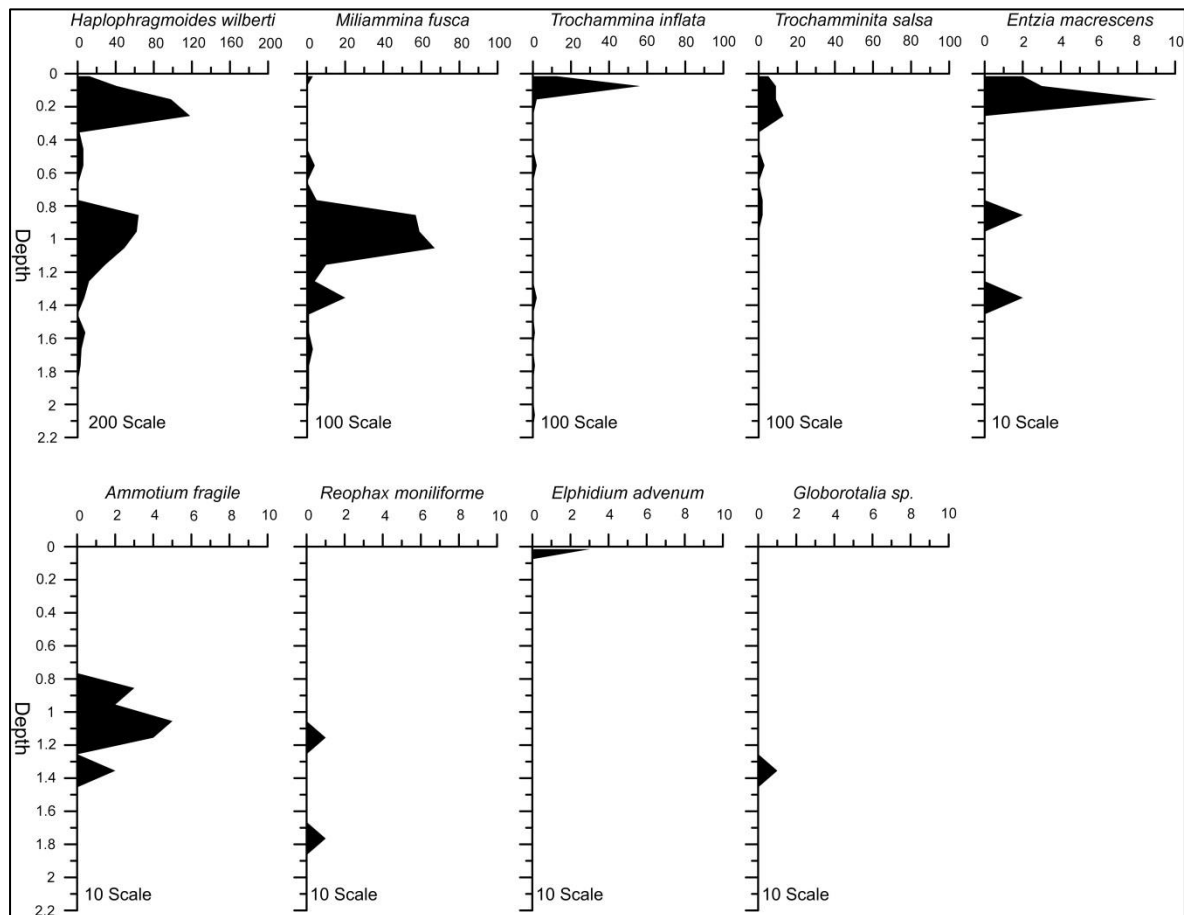


Figure 5.5 Foraminifera species present within the core, including the number and distribution throughout the core. The scales vary for different species

Haplophragmoides wilberti: An agglutinated species, *H. wilberti* is the most dominant species throughout the core. Present in all but one sample between 0 m and 1.76 m it is most dominant between 0.15 m and 0.25 m with 98 and 118 tests present respectively. *H. wilberti* is present in very low numbers between 0.35 m and 0.76 m where very few foraminifera are found overall. Between 0.85 m and 0.95 m *H. wilberti* represents the highest number of foraminifera species present with slightly higher numbers than *M. fusca* with sixty four and sixty two tests present respectively. At 1.25 m foraminifera numbers are too low to significantly evaluate the numbers of each species present although some *H. wilberti* are

present, at 1.35 m 7 *H. wilberti* tests are present equating to 20.6 % of total tests present. Below 1.35 m there are not enough foraminifera present to interpret the dominant species although a few *H. wilberti* tests were found. Along the Settlers Reserve Transect *H. wilberti* is the dominant species at 55 m it is located in a salt marsh and the *Juncus berm* in the MHW zone. In the New Zealand model for brackish-water faunas *H. wilberti* is located above the low tide zone in the intertidal zone and in salt marshes and salt meadows. It ranges from the EHWS zone to the MHW zone and has a large range of tolerable salinities from fresh water to near marine (Hayward et al., 1999).

Miliammina fusca: An agglutinated foraminifera species, *M. fusca* is one of three dominant species present in the core. Although present in low numbers at the very top of the core *M. fusca* does not become dominant until around half way down the core. At 0.85 m and 0.95 m *M. fusca* is slightly less dominant than *H. wilberti* with fifty seven and fifty nine tests present respectively. At 1.05 m *M. fusca* becomes the most dominant species with sixty seven tests present but then decreases significantly in percentage at 1.15 m with only ten tests present. At 1.25 m foraminifera numbers are too low to significantly evaluate the numbers of each species present although some *M. fusca* are present. *M. fusca* then becomes the dominant species again at 1.35 m with twenty tests present. *Miliammina fusca* is present in low numbers until 1.96 m although the numbers of foraminifera are not high enough to quantify. Along the SRT *M. fusca* is dominant between 65 m and 160 m, it is located on a sand flat and is from the MHW tidal zone to the MLW tidal zone with a low salinity measured at 160 m as 3.32 ppt with an average sediment pH of 7.3. In the New Zealand model for brackish-water faunas *M. fusca* is located in a wide zone from subtidal to intertidal and can live in salt marshes, salt meadows as well as mangrove forests. It ranges from the MHWS tidal zone to below the MLW tidal zone and has a large range of tolerable salinities from fresh water to near marine (Hayward et al., 1999).

Trochammina inflata: One of the three dominant species, *Trochammina inflata* is an agglutinated foraminifera species which appears dominantly at 0.015 m and 0.075 m, at 0.015 m there are twelve tests present which is equal with *H. wilberti* as the highest species present. At 0.075 m there are 56 *Trochammina inflata* tests present making up over 50 % of the total tests present, below 0.075 m there are very few *Trochammina inflata* tests with between one and two tests appearing sporadically every few samples. Along the SRT *Trochammina inflata* is dominant between 5 m and 50 m, with the exception of 15 m, it is located on a *Sarcocornia* sp. flat and in a low salt meadow. It is from the EHWS tidal zone to the MHWS

tidal zone with salinity levels around 17.4 ppt and an average sediment pH of 7.84. In the New Zealand model for brackish-water faunas *Trochammina inflata* is located above the low tide zone in the intertidal zone and in salt meadows and salt marshes. It ranges from the EHWS tidal zone to the MHWS tidal zone and has a large range of salinities from moderately fresh water to near marine water (Hayward et al., 1999).

Trochammina salsa: An agglutinated species, *Trochammina salsa* is not a dominant species in the core. Present in low numbers, *Trochammina salsa* is found mainly between 0.015 m and 0.25 m with between five and thirteen tests present at these locations. *Trochammina salsa* reappears three more times in very low numbers between 0.55m and 0.855m. Along the SRT *Trochammina salsa* is never a dominant species but appears in its highest numbers at 50 m and 55 m and is located on the *Sarcoconia* sp. flat, in the salt marsh, *Juncus* berm and sand flat from the EHWS tidal zone to the MHW tidal zone. In the New Zealand model for brackish-water faunas *Trochammina salsa* is located at river mouths and the very edges of estuaries in places with very low salinity at near fresh water levels. It is also found on the edges of salt marshes with tidal heights of between the EHWS tidal zone and the MSL tidal zone (Hayward et al., 1999).

Entzia macrescens: An agglutinated species, *Entzia macrescens* is present in low numbers within the core. Its highest numbers are between 0.015m and 0.15m, there are two tests present at 0.015 m and 3 tests present at 0.075 m, a maximum of nine tests are present at 0.155m. Below this *Entzia macrescens* reappears twice more at 0.855m and 1.355m with two tests present at each location. Along the SRT *Entzia macrescens* is a dominant species between 5 m and 15 m although is only the most dominant species at 15 m, it is located on a *Sarcocornia* sp. flat and low salt meadow. The salinity for *Entzia macrescens* is around 17.4 ppt and is in the EHWS tidal zone. In the New Zealand model for brackish-water faunas *Entzia macrescens* is located over a very small zone above the low tide line and in the MHWS tidal zone. It lives in salt meadows and is tolerable of a wide range of salinities although is most prominently found in near marine conditions around 30 ppt (Hayward et al., 1999).

Ammotium fragile: An agglutinated foraminifera species *A. fragile* is not present until midway down the core. *A. fragile* is not a dominant species and is present low in numbers between 0.855m and 1.355m with a maximum number of five tests present at 1.055m. Along the SRT *A. fragile* is not a dominant species and only appears in one sample at 160 m and has

only one test present. It was found in a sample below the MLW tidal zone on the sand flats where the salinity is very low, around 3.32 ppt and the sediment pH is 7.48. In the New Zealand model for brackish-water faunas *A. fragile* is a dominant species, it is located at between the MHS tidal zone and the MLW tidal zone. The salinity tolerance of *A. fragile* is brackish water midway between freshwater and marine and is not associated with any vegetation (Hayward et al., 1999).

Reophax moniliforme: An agglutinated foraminifera species, *R. moniliforme* is only present at two locations down the core, 1.15 m and 1.75 m, with one test found at each site. With such low numbers *R. moniliforme* is not a dominant species in the core. Along the SRT *R. moniliforme* is not a dominant species and only appears at two sample locations, 65 m and 100 m. This species is found on the sand flats between the MHW tidal zone and the MLW tidal zone with a average pH of 7.4. In the New Zealand model for brackish-water faunas *R. moniliforme* is a dominant species, it is located between the MSL tidal zone and the MLW zone and is predominantly subtidal. The salinity tolerance of *R. moniliforme* is restricted to brackish water and lives midway between freshwater and marine water, it is not associated with any vegetation.

Elphidium advenum: A calcareous foraminifera species, *E. advenum* only appears in the surface sample and in low numbers. *E. advenum* makes up three of the thirty seven tests present in the sample, with such low numbers it is not a dominant species in the core. Along the SRT *E. advenum* is not a dominant species, it is found in low numbers in eight samples from the 55 m to 130 m. This species is found in the *Juncus* berm and salt marsh as well as on the sand flats, it ranges from the MHW tidal zone to the MLW tidal zone and has an average sediment pH of 7.4. In the New Zealand model for brackish-water faunas *E. advenum* is a dominant species, it is located between the MHW tidal zone and the MLW tidal zone and is wide spread from intertidal to subtidal. The salinity tolerance of *E. advenum* is low; it cannot tolerate water of significantly reduced salinity so is restricted to areas of between 25 ppt to 30 ppt.

Globorotalia sp.: A calcareous planktic marine foraminifera species, there is only one test present in the core which is located at 1.355m. The core does not intercept fully marine sediments and the occurrence of *Globorotalia* sp. is unusual. It may be related to dead tests being brought in on tides or the result of liquefaction. *Globorotalia* sp. is not present along the SRT or in the New Zealand model for brackish-water faunas.

5.2.3 Species Diversity

A range of diversity indices are calculated to better define the foraminiferal distribution of the Settlers Reserve Core. The same three diversity indices used in Section 4.1.5 are applied here.

The number of species per sample down the SRC is shown in Figure 5.6 along with the number of specimens per sample for comparison. The number changes down the core in no specific pattern and is not directly linked to the number of specimens. The number of species present along the core ranges from zero to six, with the most diverse samples occurring at 0.015 m and again at 1.35 m.

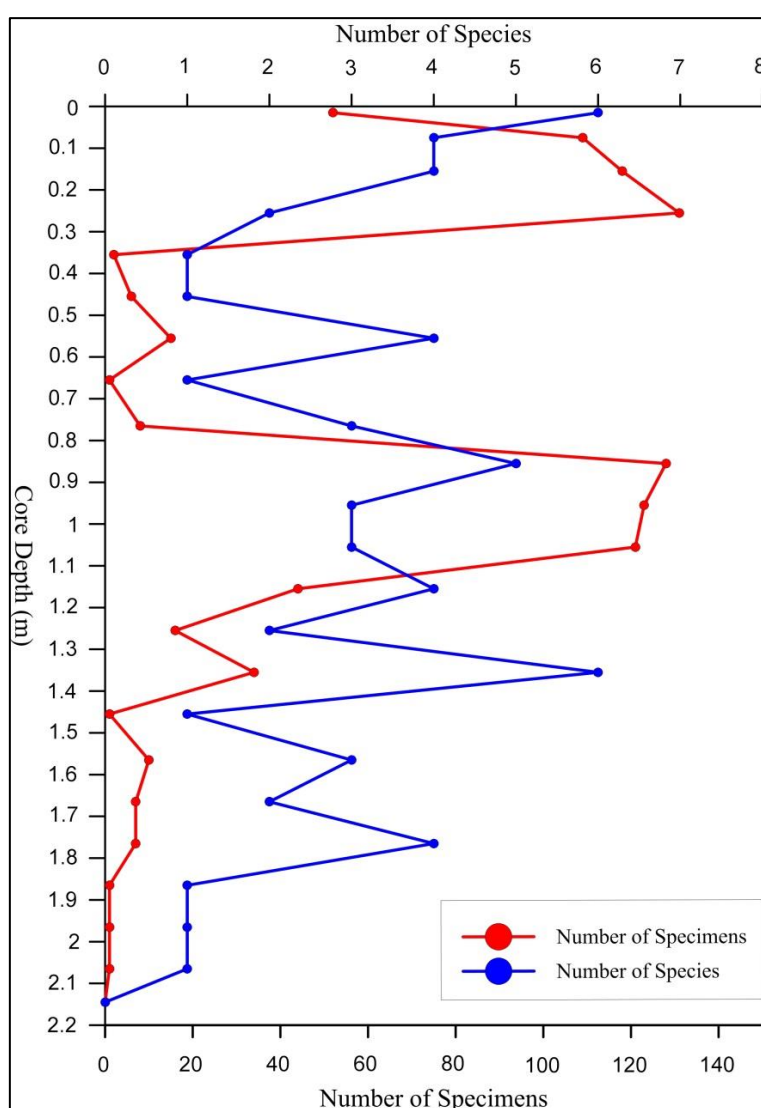


Figure 5.6. The number of species present in each sample down the core coupled with the number of specimens

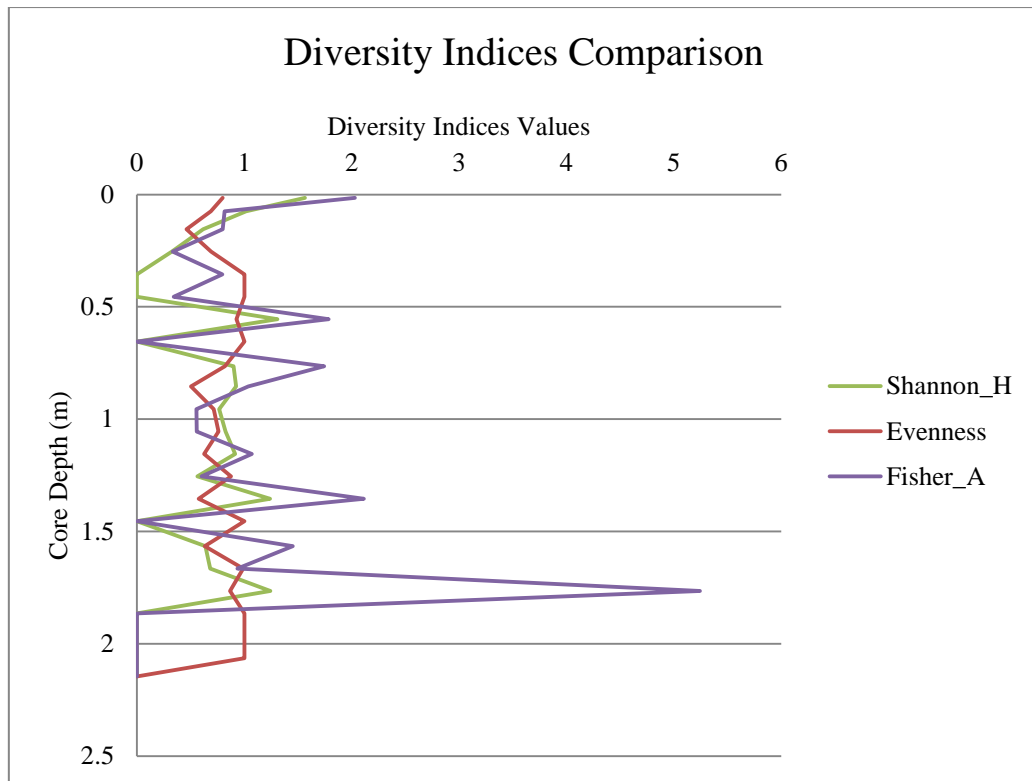


Figure 5.7. Comparison of the calculated diversity indices down the core

The diversity indices shown in Figure 5.7 are: Shannon-Weiner information function often referred to as Shannon_H, (SH), Evenness and Fisher alpha index ($F\alpha$), the calculations for which are presented in Section 4.1.5.

The Shannon-Weiner information function (SH) shows very low overall diversity, ranging from 0 to 1.57, samples with between 0 and 1 species present are given a value of 0 which affects eight of the twenty three samples. The maximum index for the SH is 1.57 which occurs at 0.015 m and the minimum index (above 0) is 0.32 which occurs at 0.25 m. The SH shows a similar pattern in values to the Fisher alpha index ($F\alpha$) where they increase and decrease at the same samples down the core. This shows they are both influenced by the same factors, although the SH has lower overall values than $F\alpha$.

Evenness is relatively high throughout the core, calculated out of 1 Evenness ranges from 0 to 1, an Evenness of 0 can only be calculated if there is no foraminifera found in a sample which affects only one of the twenty three samples. The maximum index for Evenness is 1 which occurs at seven sample sites down the core, Evenness is not affected by low numbers of tests or species present so for example at a sample site with only one test present Evenness will be calculated at 1 due to the sample having completely even numbers of the species present. This explains why Evenness is so high in these seven samples because

there are low numbers of tests present and only one species at each site. At sites with higher numbers of tests present and more than one species Evenness is lower, the minimum index (above 0) is 0.46 which occurs at 0.15 m, there are 118 tests present and four species present at this sample site.

The Fisher alpha index ($F\alpha$) shows very low overall diversity, ranging from 0 to 5.25, samples with between 0 and 1 individual tests present are given a value of 0 which affects six of the twenty three samples. The maximum index for $F\alpha$ is 5.25 which occurs at 1.76 m and the minimum index (above 0) is 0.34 which occurs at 0.25 m.

5.3 Foraminiferal Associations

5.3.1 Cluster Analysis

Bray-Curtis cluster analysis was used to establish the foraminiferal associations of the Settlers Reserve Core using dendrogram classifications as shown in Figure 5.8. Foraminiferal associations of the core are separated into sample associations (X-axis) and species associations (Y-axis), samples cluster together influenced by the species present within the samples, particularly the dominant species. Species cluster together influenced by what species occur most commonly together and can only appear in one species association. The X-axis is divided into three sample associations, grouped by the most dominant species present, *Haplophragmoides wilberti* association (H), *Haplophragmoides wilberti* – *Miliammina fusca* association (H-M) and *Trochammina inflata* association (Tn). The Y-axis is divided into three species associations, these are labelled by numbers, 1, 2 and 3 and are not grouped by the most dominant species present in the core.

5.3.1.1 Sample Associations

***Haplophragmoides wilberti* species association:**

Fauna: This sample association is dominated by *Haplophragmoides wilberti* (83 % – 90 % mean 86.5 %) and common secondary species are *Entzia macrescens* and *Trochamminita salsa* (7 % – 10 % each).

Sediment: Silty medium sand

Diversity: Very low; SH = 0.3 – 0.6 (mean 0.45), E = 0.5 – 0.7 (mean 0.6), $F\alpha$ = 0.3 – 0.8 (mean 0.55)

Core Location: Upper core, 0.15 m – 0.25 m

***Haplophragmoides wilberti* – *Miliammina fusca* sample association:**

Fauna: This sample association is dominated by *Haplophragmoides wilberti* (21 % - 50 % mean 45.5 %) and *Miliammina fusca* (23 % - 59% mean 46.9 %) and common secondary species are *Ammotium fragile* and *Entzia macrescens* (2 % - 10 % each).

Sediment: Clayey silt – silty medium sand

Diversity: Very low; SH = 0.8 – 1 (mean 0.9), E = 0.5 – 0.8 (mean 0.6), F α = 0.6 – 2.9 (mean 1)

Core Location: Mid-lower core 0.85 m – 1.35 m

***Trochammina inflata* sample association:**

Fauna: This sample association is dominated by *Trochammina inflata* (30 % - 51 % mean 40.5 %) and common secondary species are *Haplophragmoides wilberti* (30 % - 37 % mean 33.5 %) *Trochammina salsa*, *Elphidium advenum*, *Miliammina fusca* and *Entzia macrescens* (6 % - 10 % each).

Sediment: Silty medium sand

Diversity: Very low – low diversity; SH = 1 – 1.6 (mean 1.3), E = 0.7 – 0.8 (mean 0.75), F α = 0.8 – 2 (mean 1.4)

Core Location: Upper core 0 m – 0.06 m

5.3.1.2 Species Associations

Species can only appear in one species association per dendrogram classification and this is determined by the species which they appear most commonly with. The dominant species in species associations can differ from those which appear in the sample associations.

Species Association 1:

Fauna: This species association is dominated by *Ammotium fragile* with secondary species *Reophax moniliforme* and *Globorotalia* sp. All species occur in low percentages within the core representing (2 % - 9 % each).

Sediment: Clayey silt – silty medium sand

Distribution: Species association 1 occurs at a depth of 0.85 m to 1.35 m, *A. fragile* occurs throughout this segment of core, *R. moniliforme* occurs at 1.15 m down core and *Globorotalia* sp. occurs at 1.35 m down core.

Species Association 2:

Fauna: This association is dominated by both *Haplophragmoides* and *Miliammina fusca*, there are no secondary species.

Sediment: Clayey silt – silty medium sand

Distribution: Species association 2 occurs between 0 m and 1.35 m depth, *H. wilberti* is present at all locations in this segment of core while *M. fusca* is present at 0 m then between 0.85 m and 1.35 m.

Species Association 3:

Fauna: This association is dominated by *Trochammina inflata* with the secondary species *Elphidium advenum*, *Entzia macrescens* and *Trochamminita salsa*.

Sediment: Sandy silt – silty medium sand

Distribution: Species association 3 occurs between 0 m - 0.25 m then at 0.85 m and again at 1.35 m depth, *Trochammina inflata* is present between 0 m - 0.14 m and then at 1.35 m, *Elphidium advenum* is only present at 0 m, *Entzia macrescens* is present between 0 m – 0.15 m then at 0.85 m and again at 1.35 m, *Trochamminita salsa* is present between 0m – 0.25 m then at 0.85 m .

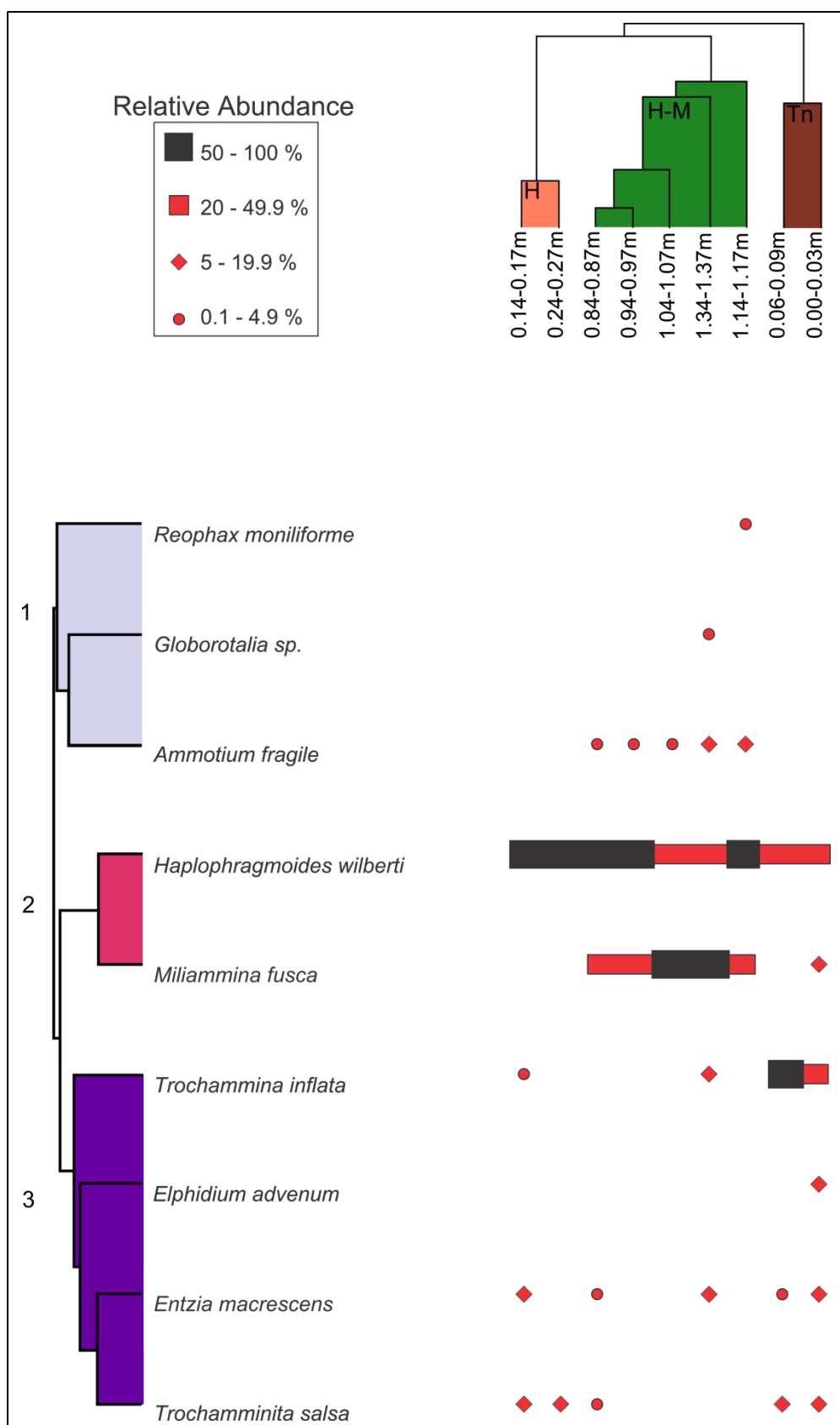


Figure 5.8. Dendrogram classification of the benthic foraminifera sample associations present within the Settles Reserve Core produced by Cluster Analysis using Bray-Curtis distance and species associations. H = *Haplophragmoides wilberti* association, M = *Miliammina fusca* association and Tn = *Trochammina inflata* association. The Y-axis species are not grouped or coloured into traditional species associations

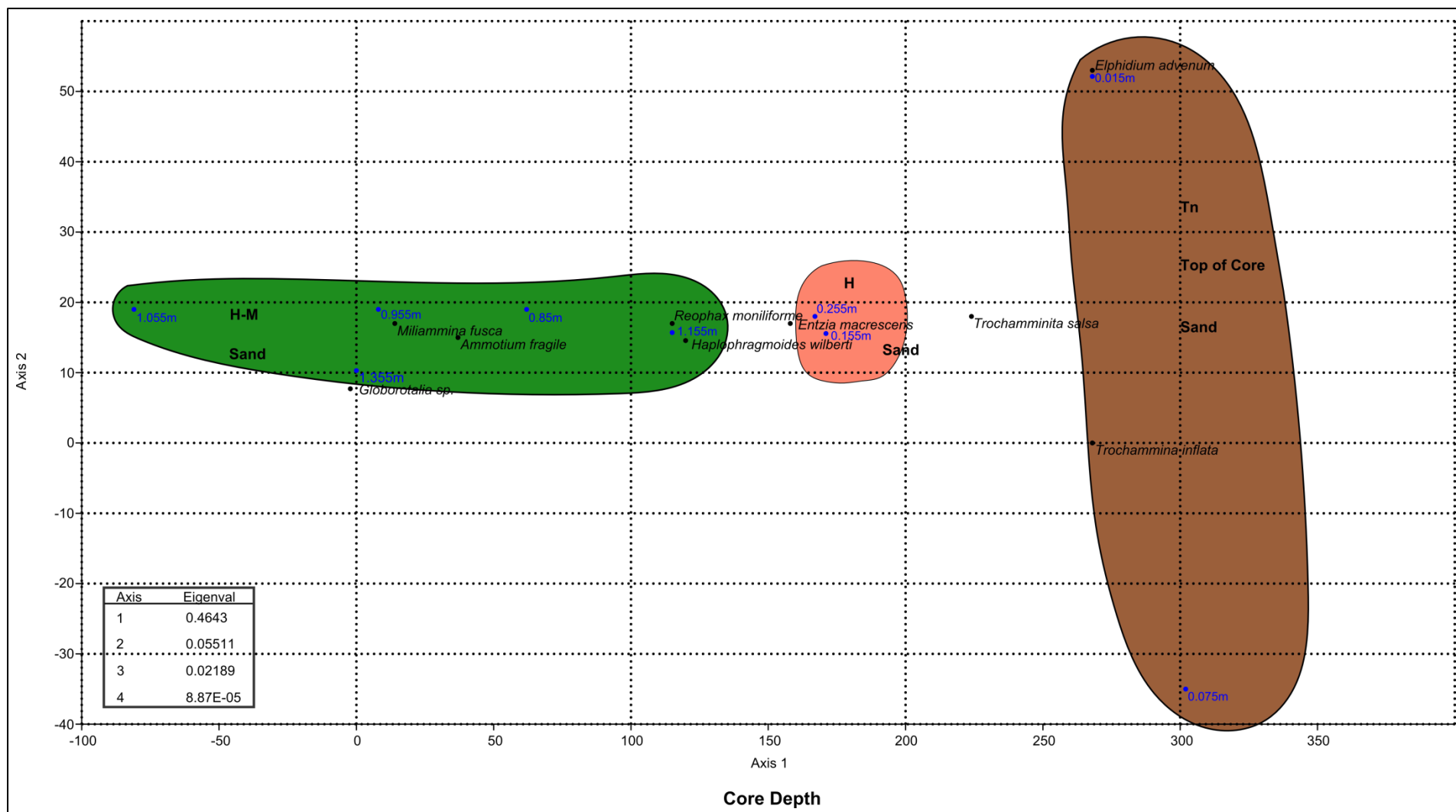


Figure 5.9. A two dimensional configuration of the foraminifera species and core depths down the Settlers Reserve Core produced by Detrended Correspondence Analysis. The axes group the depths and foraminifera species together by shared environmental factors. The Eigenval value for Axis 2 is extremely low so there is no significant environmental association of the species and sample distribution in the Y axis. The Eigenval value of 0.443 for Axis 1, although not high, shows a moderate association of species and core depth. The sample association codes are: H-M = *Haplophragmoides wilberti* - *Miliammina fusca* (green), H = *Haplophragmoides wilberti* (pink), Tn = *Trochammina inflata* (brown).

5.4 Detrended Correspondence Analysis

The core samples can be grouped together because they share common properties such as tidal depth, sediment size or vegetation habitat. Figure 5.9 was created using Detrended Correspondence Analysis (DCA), the same type of analysis used in Figure 4.8 (Section 4.2.2). The environmental factors that cause the grouping of the samples are harder to identify with the SRC than the SRT because the core samples are not taken from the modern environment but are instead from past environments and we cannot see where about on the surface they would have been located today. The same samples have been included in this analysis as those included in Section 5.3.

The only axis with an Eigenval value which is representative of a moderate correlation is Axis 1 with a value of 0.4634. Although the value is not extremely strong, Axis 1 can be correlated with core depth when looking at the placement of the species and the core depths, although not in exact depth order. The samples from the top of the core are toward the right side of Axis 1 and samples from deeper in the core are toward the left side of Axis 1.

The *Trochammina inflata* sample association (brown) and includes the top two samples and is associated with sandy sediments. The *H. wilberti* sample association (pink) is also made up of sandy sediment and includes samples from near the top of the core, (0.15 m and 0.25 m). The *H. wilberti* - *M. fusca* sample association (green) is made up of sandy sediments and includes the middle – lower samples (0.85 m – 1.35 m). All DCA sample associations correlate with those established by the cluster analysis in Figure 5.8 confirming these associations.

5.5 Model Core Tidal Heights

The core was collected to achieve the aim of applying the distribution of modern foraminifera and tidal heights to faunas present in core samples to determine the development of the southern Avon-Heathcote Estuary and identify any historic coseismic deformation events. To achieve this aim a model was created using the modern foraminifera samples and the core samples to model how tidal height has changed in the Avon-Heathcote Estuary over time from which it can be told if it was constant or interrupted by possible coseismic deformation.

C2 was used to create the model, this is a program designed for analysing palaeoenvironmental data with the ability to compare data and create models, the normalised data was used to negate against human error when picking the foraminifera tests. Firstly a training set had to be created to identify the ideal tidal height of each of the modern day species found along the Settlers Reserve Transect. The two components used to create this training set were the foraminifera species present and the tidal height of each sample site from the SRT this was modelled using the statistical method of weighted averaging. This training set used to create a model which reconstructed the core and calculated where the core samples would have been located on the modern day transect according to tidal height. To create the reconstruction model the foraminifera data and tidal heights from the SRT were selected again, along with the foraminifera data from the core to run a reconstruction with. For the model to work samples with zero foraminifera tests must be excluded from the reconstruction. The values given for the reconstructed model were transferred into Microsoft Excel to develop a sea-level curve using the formula $S = H - I$. S is the palaeo-MSL, H is the sample height relative to MSL and I is the depth in the core, once S is found the surveyed elevation is taken away from S to reconstruct paleo-sea-level. This reconstruction gives insight into the foraminifera, sedimentation and sea-level history of the Settlers Reserve area in the Avon-Heathcote Estuary.

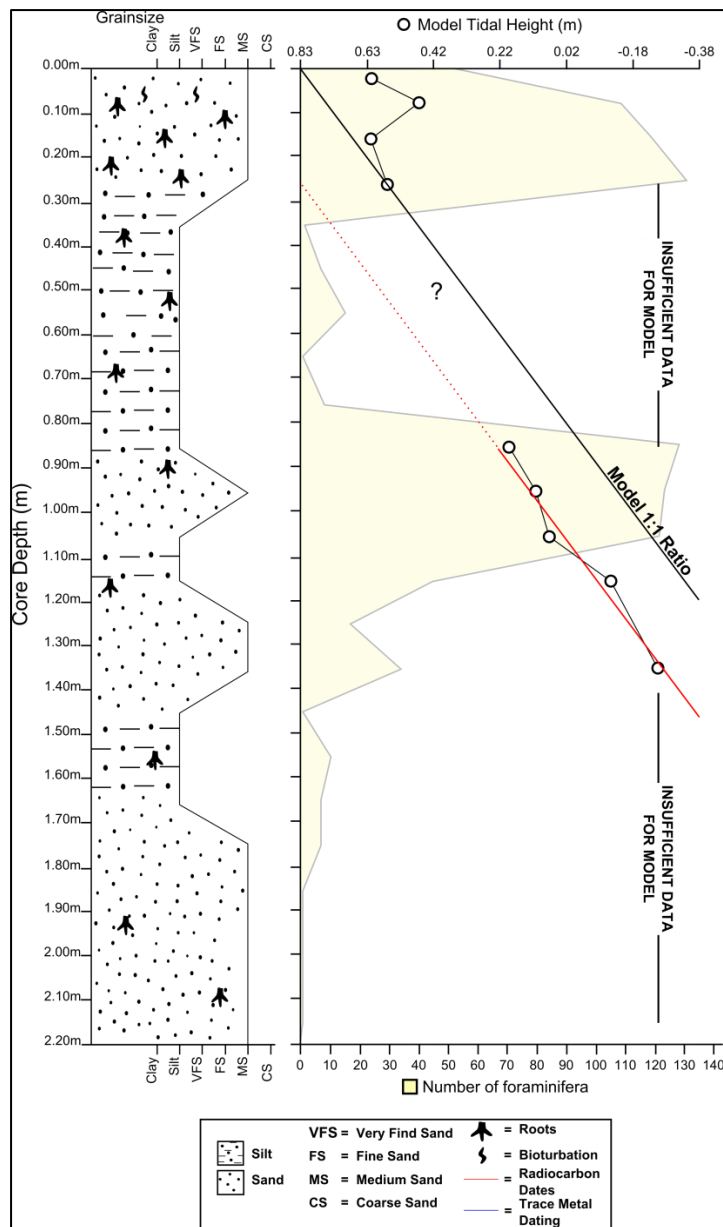


Figure 5.10. Graph showing the reconstructed tidal heights of the samples taken from the Settlers Reserve Core. The X-axis refers to the metres below the tidal height the surface of the core was taken from (0.83m above Sea Level).

Multiple models were created using different data sets, it was found that both the normalised data and raw data create a similar result, however, the normalised results do not include and outlier marker at 1.25 m where foraminifera are in quantities too low to give an accurate result. Calcareous foraminifera were removed from the training set data to match the core data which is depleted in calcareous foraminifera, this only created slightly different results by ~ 0.02 m which has no significant effect on the model.

The sea-level reconstruction is shown in Figure 5.10, of the twenty three samples collected from the core only nine contained enough foraminifera to use in the reconstructed model so the data is not continuous creating many gaps in the model. The perfect model

would show all samples lining up on the black line which would indicate a constant rate of sedimentation over time. The model instead shows changes in the rate of either sedimentation or sea-level change or both. The top two samples, 0.015 m and 0.075 m, plot above the model line, while the next consecutive samples, 0.15 m and 0.25 m, plot near the model line. There is a lack of foraminiferal data between 0.25 m and 0.85 m creating a gap in the model. When foraminifera rich samples reoccur further down the core they all plot below the model line for a constant rate of change, they instead plot parallel to the model line. This indicates that there was either a period of gradual change in sea level or sedimentation or a sudden event causing the displacement from the model. Below 1.35 m there was not enough data collected to include in the model.

5.6 Trace Metal Results

The main objective for analysing the trace metals present in the core is to help gauge an understanding of the age profile the core by identify key changes in trace metal concentration. Changes in trace metal concentration can help to identify the arrival of European settlers, the introduction of key industries and diversion of waste drainage all of which are well dated in the literature (Deely 1991). The location of where increased enrichment of certain trace metals begins can be traced back to the beginning of an industry which can be dated. Where trace metal enrichment declines can be traced to the diversion of waste materials from the Heathcote River and decline of some industries. Trace metal analysis was completed on all twenty three samples taken from the SRC, the results for which are presented in Figure 5.11, Figure 5.12, and Figure 5.13. Trace metals are in order of atomic weight.

Vanadium (V): Vanadium shows a general increase in concentration progressively up the core. General enrichment of vanadium starts from 1.15 m, the concentration increases up the core until 0.15 m from where it decreases sharply over the remainder of the core. The maximum concentration of vanadium occurs at 0.45 m with a concentration of 38 mg/kg and the minimum concentration is 16 mg/kg found at 0.015 m.

Chromium (Cr): Chromium shows a general increase in concentration progressively up the core. General enrichment of chromium starts from 1.15 m, the concentration increases up the core until 0.15 m from where it decreases sharply over the remainder of the core. The maximum concentration of chromium occurs at 0.55 m with a concentration of 25 mg/kg and the minimum concentration is 12 mg/kg occurring at 0.015 m.

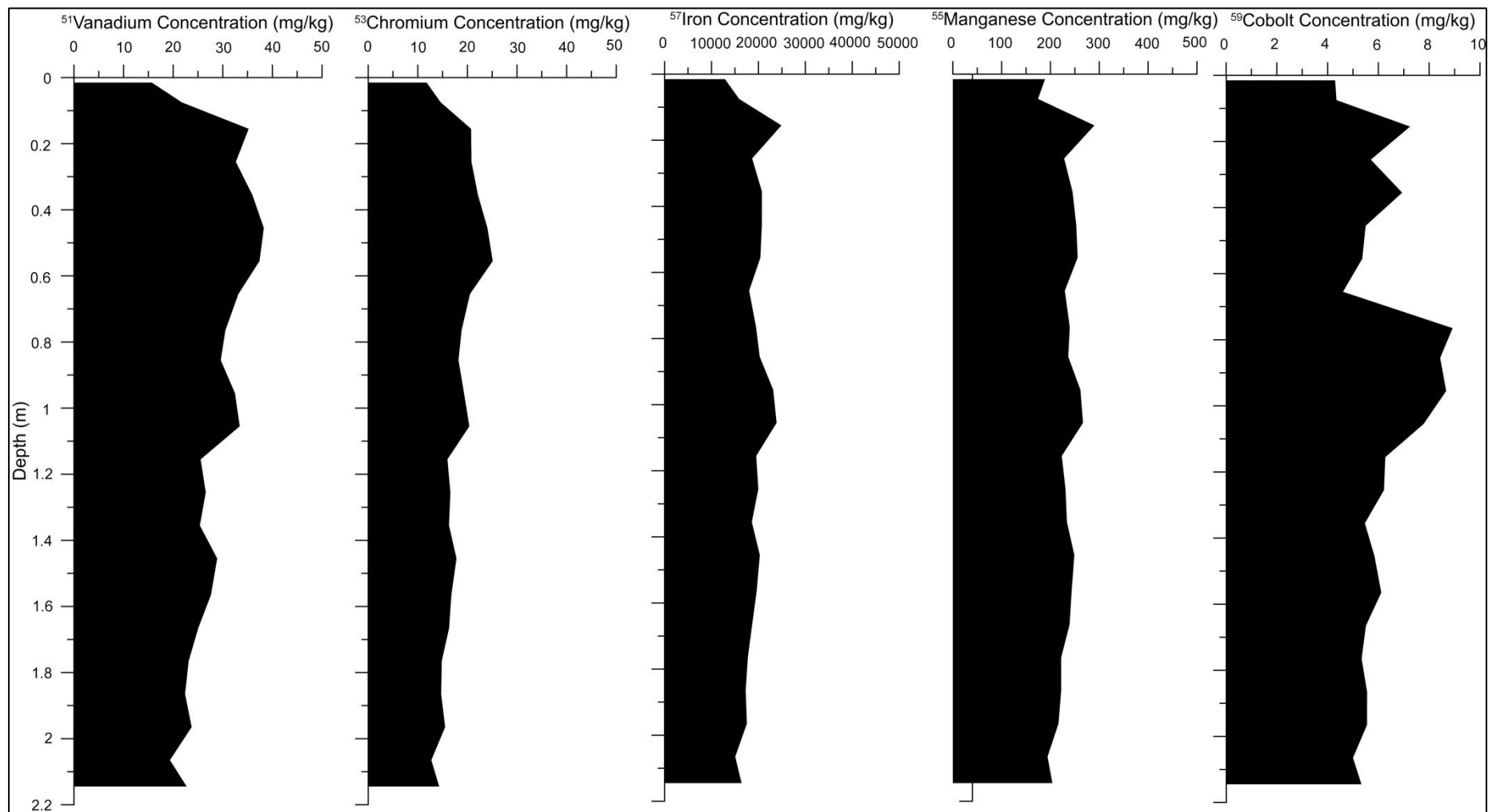


Figure 5.11. Graphs of trace metal concentrations, vanadium, chromium, iron, manganese, cobalt.

Manganese (Mn): Manganese shows a general increase in concentration progressively up the core. General enrichment of manganese starts from 1.15 m, the concentration increases up the core until 0.15 m from where it decreases sharply over the remainder of the core. The maximum concentration of manganese occurs at 0.155m with a concentration of 290 mg/kg, the minimum concentrations are 174 and 189 mg/kg found in the top 9 cm of the core.

Iron (Fe): Iron has the highest concentration of any of the trace metals analysed, iron increases in concentration progressively up the core. General enrichment of iron starts from 1.15 m, the concentration increases up the core until 0.15 m from where it decreases sharply over the remainder of the core. The maximum concentration of iron occurs at 0.155m with a concentration of 15046 mg/kg, the lowest consecutive iron values are found in the top 9cm of the core with concentrations of 9687 and 7808 mg/kg.

Cobalt (Co): Cobalt changes concentration throughout the core, general enrichment of cobalt starts from 1.15 m, the concentration increases up the core until 0.76 m where it decreases sharply and is variable to the top of the core. The maximum concentration of cobalt occurs at 0.76 m with a concentration of 9 mg/kg, the minimum concentration is 4 mg/kg occurring between 0.075 m and 0.015 m.

Nickel (Ni): General enrichment of nickel starts from 1.15 m, the concentration increases up the core until 0.15 m from where it decreases sharply over the remainder of the core. The maximum concentration of nickel occurs at 0.35 m with a concentration of 17 mg/kg, the minimum concentration is 9 mg/kg at 0.015 m.

Copper (Cu): Copper shows a general increase in concentration progressively up the core. General enrichment of copper starts at 1.15 m, the concentration increases up the core until 0.35 m from where it decreases sharply over the remainder of the core. The maximum concentration of Copper occurs at 0.35 m with a concentration of 12 mg/kg and the minimum concentration occurs at 2.06 m with a concentration of 4 mg/kg.

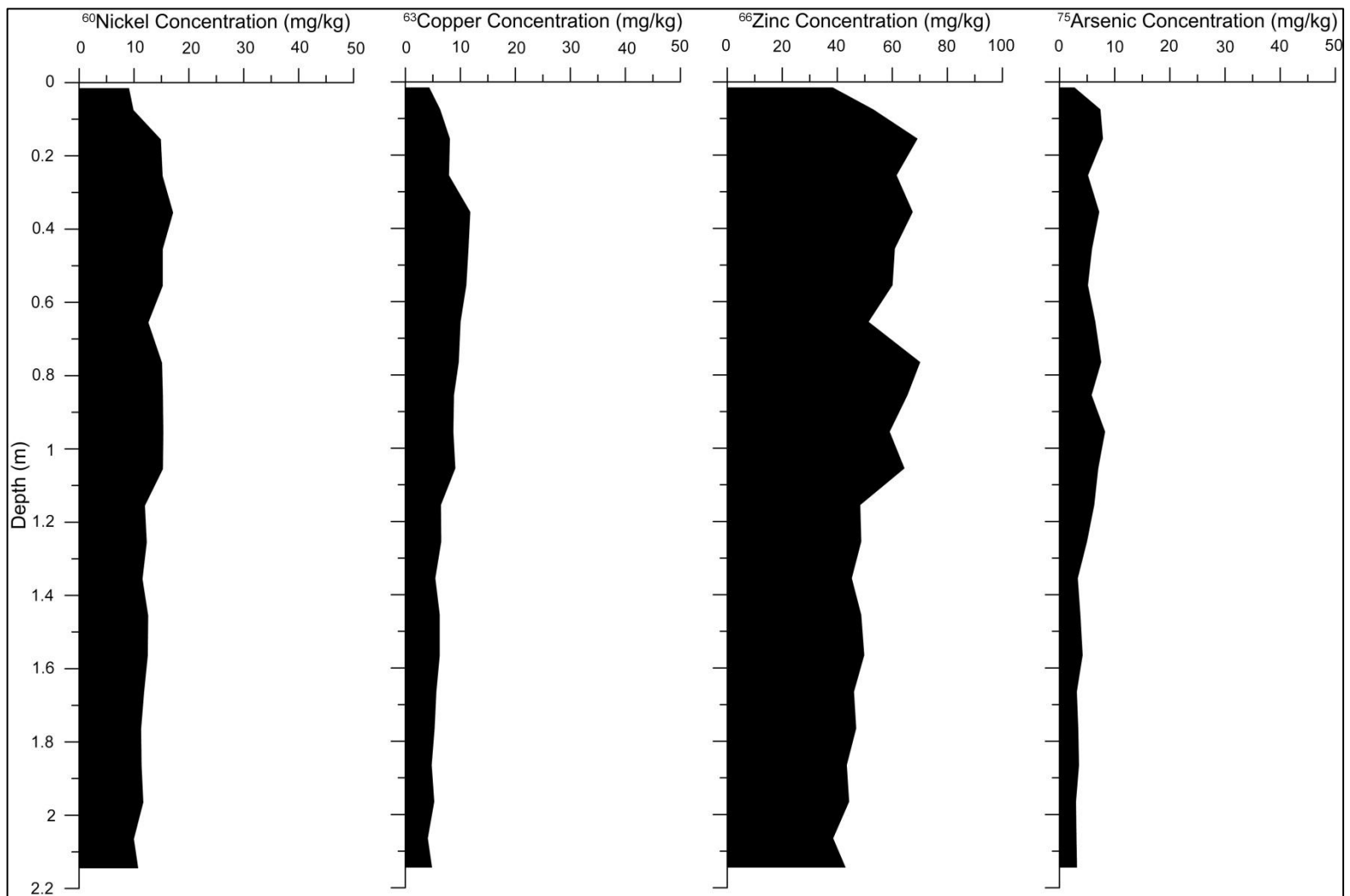


Figure 5.12. Graphs of trace metal concentrations , nickel, copper, zinc and arsenic.

Zinc (Zn): Zinc shows a general increase in concentration progressively up the core, the general enrichment of zinc starts at 1.15 m, the concentration mainly increases up the core until 0.15 m from where it decreases sharply for the remainder of the core. The maximum concentration of zinc occurs at 0.76 m with a concentration of 70 mg/kg and the minimum concentration occurs between 0.06 m and 0.015 m with a concentration of 38 mg/kg.

Arsenic (As): Arsenic follows a general increase in concentration progressively up the core. General enrichment of arsenic starts at 1.35 m, the concentration varies at higher values up the core until 0.06 m from where it decreases sharply over the remainder of the core. The maximum concentration of arsenic occurs at 0.95 m with a concentration of 8 mg/kg and the minimum concentration occurs between 0.065 m and 0.015 m with a concentration of 2 mg/kg.

Silver (Ag): Silver shows a different pattern to many of the other trace metals, very low concentrations of silver are seen throughout the core until 0.25 m where increased enrichment starts and continues to increase until the top of the core. The maximum concentration of silver occurs at the top of the core at 0.015 m with a concentration of 0.25 mg/kg and the minimum concentration occurs at 2.06 m with a concentration of 0.02 mg/kg.

Cadmium (Cd): The concentration of enrichment for cadmium is below the detection level for the ICPMS method.

Antimony (Sb): General enrichment of antimony starts at 1.15 m, the concentration mostly increases up the core until 0.15 m from where it decreases sharply over the remainder of the core. The maximum concentration of antimony occurs at 0.45 m with a concentration of 0.36 mg/kg and the minimum concentration occurs at 2.06 m with a concentration of 0.12 mg/kg.

Lead (Pb): General enrichment of lead starts at 1.15 m, the concentration increases up the core until 0.15 m from where it decreases sharply over the remainder of the core. The maximum concentration of lead occurs at 0.55 m with a concentration of 27 mg/kg and the minimum concentration occurs at 0.015 m with a concentration of 9 mg/kg.

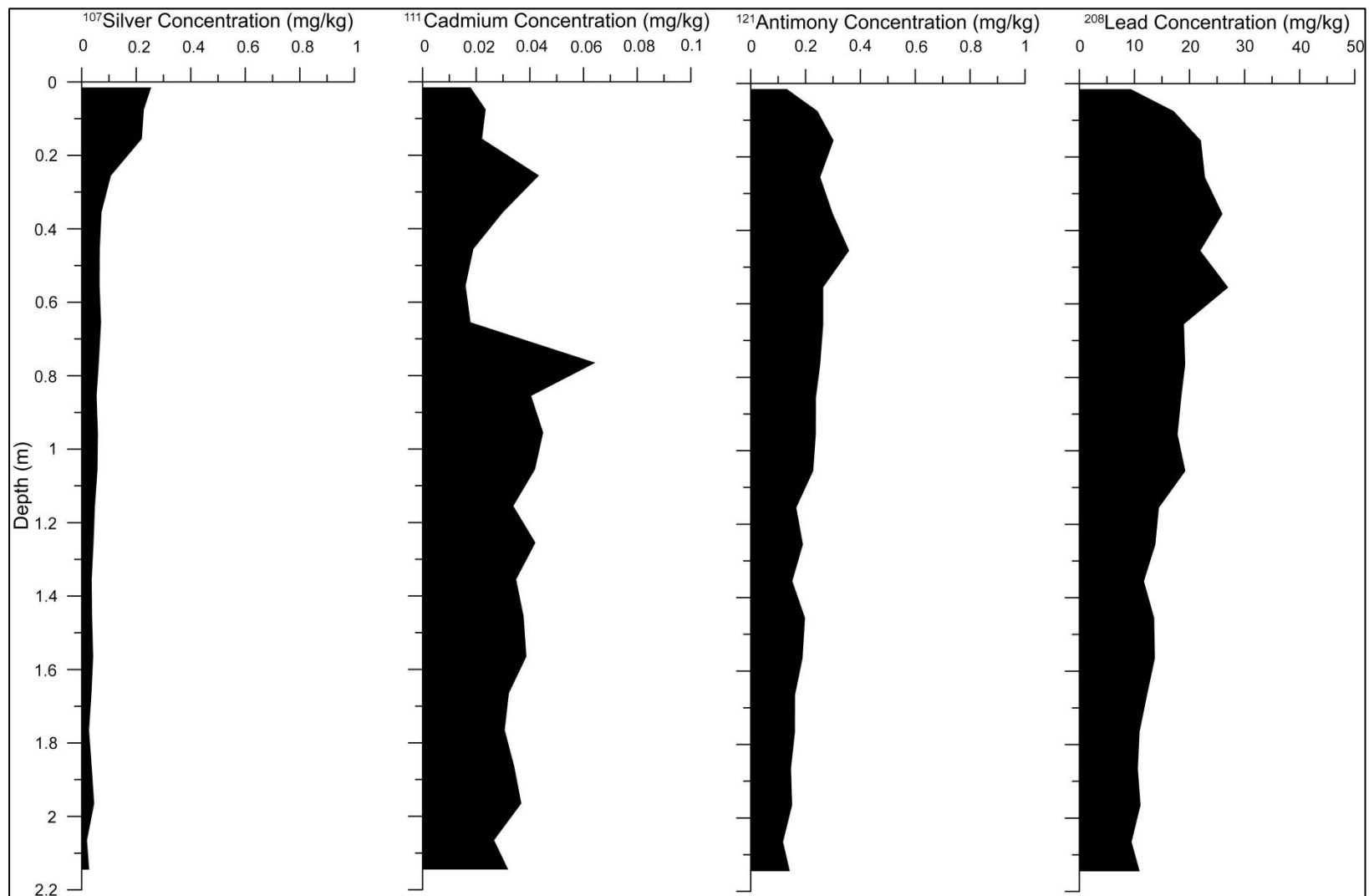


Figure 5.13. Graphs of trace metal concentrations, silver, cadmium, antimony and lead.

5.7 Carbon and Nitrogen Analysis

The core samples were analysed for carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) stable isotopes (reported in parts per thousand ‰) as well as the percentage of organic carbon and nitrogen within the core. Stable isotope analysis of the core can be used to trace the origin of the sediments from either terrestrial or marine origins. These data can help establish how Settlers Reserve developed over time and can be correlated with the trace metal analysis to give general time periods. Total organic carbon (% C) and nitrogen percentages (% N) are influenced by changes in land use, such as an increase in farming and agriculture or industry. These can be directly correlated with the trace metal analysis providing further insight into estuary development and sediment dating. The results for isotope analysis are presented in Figure 5.14.

The $\delta^{13}\text{C}$ values are negative and range between -24.99 ‰ and -27.96 ‰, they become increasingly more negative progressively up the core until 0.35 m after which they become more enriched. Between 2.15 m and 0.35 m the $\delta^{13}\text{C}$ values decrease from -25.69 ‰ to -27.96 ‰ and above this the values increase to -24.99 ‰.

The $\delta^{15}\text{N}$ values are positive and range between 0.33 ‰ and 4.56 ‰, there is no consistent trend in these values along the length of the core (Figure 5.14). Between 2.15 m and 0.25 m $\delta^{15}\text{N}$ values remain consistently between 1.66 ‰ and 3.54 ‰, these increase between 0.25 m and 0.075 m to 4.56 ‰ and then decrease between 0.075 m and 0.015 m to 0.33 ‰.

The % C values range between 0.35 % and 2.86 %, they increase progressively up the core until 0.25 m after which they decrease. Between 2.15 m and 0.25 m % C values increase from 0.35 % to 2.86 % and then decrease between 0.25 m and 0.015 m to 0.49 %.

The % N values range between 0.02 % and 0.18 %, they increase progressively up the core until 0.25 m after which they decrease. Between 2.15 m and 0.25 m % N values increase from 0.03 % to 0.18 % and then decrease between 0.25 m and 0.015 m to 0.02 %.

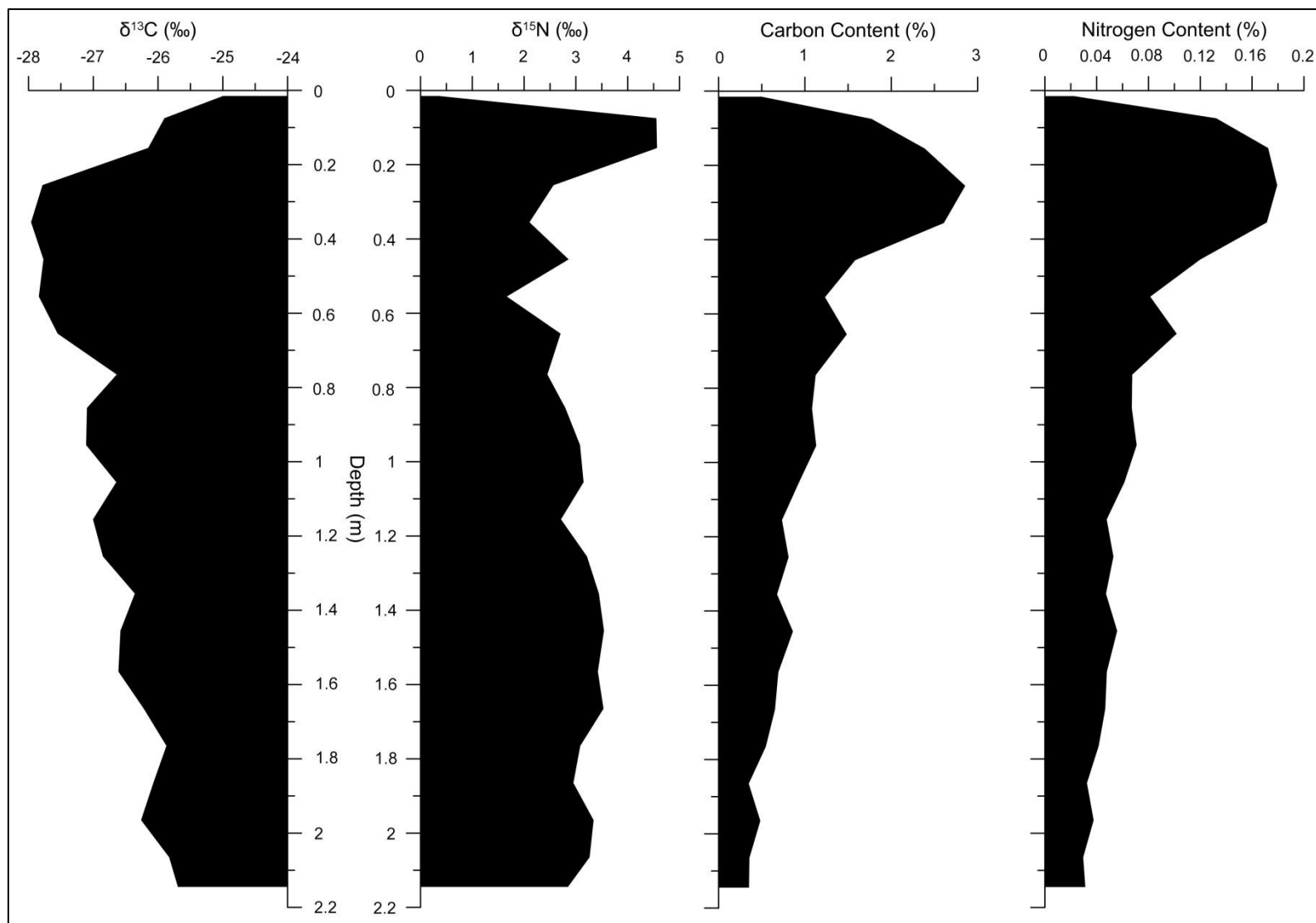


Figure 5.14. Isotope analysis of the Setters Reserve Core including results for Delta 13 Carbon ($\delta^{13}\text{C}$), Delta 14 Nitrogen ($\delta^{15}\text{N}$), Percentage of Carbon (%C) and Percentage of Nitrogen (%N).

5.8 Chapter Summary

Chapter 5 contains the results of the data collected from the core collected in the Avon-Heathcote Estuary at Settlers Reserve. Foraminifera numbers vary throughout the core they found in the highest concentrations in the top 0.25 m and then from 0.85 m to 1.35 m. The foraminifera found in the core show low overall diversity with only nine species present in the core although three species are dominant. The reconstructed model shows that there has not been a constant rate of sedimentation over the time period that the core covers. The trace metal results showed that the nearly all heavy metals increased in concentration from 1.20 m and then decreased sharply from 0.15 m with only silver showing a different pattern. The isotope and total organic carbon analysis correlates well with the trace metal results showing the same profile of enrichment pattern with increasing concentrations up the core followed by a decrease in the 0.15 m. In the discussion the geochemistry data will be used to develop an age model, and following this the reconstructed foraminifera model can be interpreted.

Chapter 6 Discussion

The foraminiferal samples collected from Settlers Reserve and Bridge Street have enabled the interpretation of the current foraminiferal distribution of the Avon-Heathcote Estuary and established the effects of the recent local seismic activity on this foraminifera distribution. A core collected at Settlers Reserve has provided some insight into the foraminiferal history of the AHE and possible past coseismic deformation events. Chapter Six discusses the findings of this study.

6.1 Modern Foraminiferal Data

The modern foraminiferal samples collected from the Avon-Heathcote Estuary include both the Bridge Street and Settlers Reserve samples collected in June 2011 and February 2013 and the Settlers Reserve Transect collected in June 2013. Both of these sets of data help to indicate the foraminiferal species present in the AHE and their distribution.

6.1.1 Foraminifera Contributions to the Avon-Heathcote Estuary

This study contributes new information to the knowledge of the foraminiferal species and distributions present in the Avon-Heathcote Estuary. Previous studies on the foraminifera of the AHE are limited to Pearson (2009), who sampled sites around the entirety of the AHE, while this study focused on the detailed sampling of one area and the less detailed sampling of another. The two sites from this study were limited mainly to the high intertidal zone while Pearson (2009) sampled throughout all tidal zones.

The two studies have yielded slightly different species results which is likely due to the difference in sampling locations as well as the sediment influx caused by the liquefied sediments introduced during the February 2011 Christchurch Earthquake. Of the twenty eight species identified by Pearson (2009) only eleven of those were also identified in this study leaving seventeen not found. These unidentified species were found in central locations of the AHE such as large channels and the central mudflats that were not sampled in this study. The most notable species that was not identified in this study was *Nonionellina flemingi*, this species was dominant in three samples across the AHE in the Pearson (2009) study. The sample sites that *Nonionellina flemingi*, however, were in more central estuarine areas that were not sampled in this study.

There are eight species identified by this study can be added to the known foraminifera species distribution of the AHE, these are: *Ammobaculites exiguus*, *Ammonia beccarii*, *Ammotium fragile*, *Amphicoryna* sp., *Buccella frigida*, *Entzia macrescens*, *Miliolinella* sp., and *Reophax moniliforme*. The species added to the list of known foraminifera in the AHE were mostly found in low quantities totalling less than ten and at few samples locations. The exception to this is *Entzia macrescens* which is a dominant species found within the AHE, it was found mainly in the *Sarcocornia* sp., low salt meadow located in EHWS and MHWS tidal zones.

There were two fully marine species, *Cassidulina carinata* and *Lenticulina australis*, identified in this study which was not identified in Pearson's (2009) study. These species were found in samples collected in June 2011 but were not found in the February 2013 samples. It is likely that these foraminifera were residing in older marine sediments deep below the surface and were ejected at the surface as a result of the liquefaction which occurred during the February 2011 Christchurch Earthquake. These species would not be considered to occur naturally in the AHE and should not be added to the list of known foraminifera in the Estuary.

6.1.2 Foraminiferal Response to Earthquake Deformation

Chapter 3 quantifies the change in the foraminiferal species distribution between June 2011 and February 2013 following the coseismic deformation of the Avon-Heathcote Estuary. Foraminiferal samples collected from the northern section of the AHE at Bridge Street and samples collected from the southern section of the AHE at Settlers Reserve were used for this comparison.

It was hypothesised that seismic deformation causing both uplift and subsidence around Avon-Heathcote Estuary would change the foraminiferal species distribution of the Estuary. After calculating changes in species richness and abundance between samples collected in June 2011 and February 2013 it was found that there have been no statistically significant changes to the foraminiferal distribution of the Avon-Heathcote Estuary during this time period. At Bridge Street the dominant foraminiferal species at each sample location were expected to migrate landward in response to the subsidence experienced in the area. At Settlers Reserve the dominant foraminiferal species were expected to migrate seaward in response to the uplift experienced in the area.

The lack of foraminiferal distribution changes over the period of this study is likely to be linked to low rates of sedimentation which are currently around 0.5 cm per year (Deely, 1991, Hayward et al., in prep 2014) although this varies throughout the Avon-Heathcote Estuary. For example, at Bridge Street where subsidence is known to have occurred sediment accumulation is not yet apparent (Cochran et al. 2014). The Bridge Street and Settlers Reserve transect surface samples were collected to a depth of 1 to 2 cm and due to the low sedimentation rates this resulted in sediment being sampled from multiple years of deposition both prior to and post the Canterbury Earthquake Sequence. Foraminiferal tests remain in the sediment once dead so the tests that were picked were likely to be a combination of dead tests from multiple years of sedimentation. As there were very few live foraminifera present in any of the samples there is no indication given of a new foraminiferal distribution post coseismic deformation from the Christchurch Earthquake Sequence.

Fossilised foraminifera assemblages record changes after large environmental disturbances. A foraminiferal assemblage record of a disturbance comprises of the assemblage prior to the disturbance followed by a disturbance deposit and then a post-disturbance deposit (Alve 1999). Foraminifera can be slow to colonise new habitats after environmental disturbances when in low energy environments, it can take anywhere from one year to several years (Alve 1999). As this is a study of modern sediment collected over a geologically short period of time (two years) this may not be enough time for recolonization to take place as the sediment is likely still disturbed.

There is evidence from other studies that suggests that foraminifera can be slow to recolonize after a disturbance event. Research by Hess et al., (2001) studied the recolonization of benthic foraminifera in the South China Sea following the volcanic eruption of Mt Pinatubo in 1991. The eruption covered the sea floor in a layer of ash smothering the foraminifera population. The results showed that recolonization took place slowly over the study period of 7 years with different species recolonizing at different rates and the composition of the species was likely to continue changing after the study concluded.

Although there are no statistically significant changes in foraminifera distribution across the Avon-Heathcote Estuary sample site BSNS-Z3 shows that isolated changes may have taken place. The dominant species in the sample changed from *Entzia macrescens* in June 2011 to *Miliammina fusca* in February 2013, this shows that *M. fusca* is migrating landward at this location as initially expected. The subsidence in Bridge Street area has

caused a landward shift in the tidal zones, as foraminifera species are highly specialised to their environmental parameters *E. macrescens* is no longer in its ideal environment between EHWS and MHWS within the *Sarcocornia* salt meadow. The new tidal zone between MHW and MSL is better suited to *M. fusca* as it is no longer exposed at high tide for long periods of time. As this is the only sample which has shown this response to the change in tidal zones it cannot be said that foraminifera have shifted between 2011 and 2013 and instead it is likely that *M. fusca* is a species able to react faster to environmental changes than more specialised species.

Research undertaken by Hayward et al. in prep (2014) at the northern end of the Avon-Heathcote Estuary found similar results to this study. The research was conducted at the mouth of the Avon River 400 m downstream from the Bridge Street sample location of this study. Hayward et al., in prep (2014) collected samples along a transect over a 33 month period post deformation and concluded that the faunal composition along the transect changed slowly following the subsidence. The foraminiferal surface samples also indicated that there was no significant change in elevation estimates which were calculated using a Modern Analogue Technique (MAT) (detailed in Hayward et al., 2004c). Other findings include that only the species *Trochammina salsa* migrated landward as was expected in this area. In this thesis it was not *T.salsa* that migrated landward but instead *Miliammina fusca*, this result still shows that some species have begun migrating although so slowly that the results are not yet considered significant.

Although there is currently no significant foraminiferal evidence of the deformation of the Avon-Heathcote Estuary both Cochran et al., (2014) and Hayward et al., in prep (2014) find evidence of deformation by the response of marshland vegetation. Vegetation zones shifted in both the uplifted (seaward) and subsided (landward) areas of the Estuary enabling the extent of vertical displacement to be quantified using vegetation shifts. The issue with using vegetation as an indicator of coseismic deformation is that the plants are unlikely to be preserved so this method can only be used in modern day settings. Methods using foraminifera can be applied in both modern settings and ancient settings as foraminifera can be preserved in the fossil record.

6.1.3 Settlers Reserve Transect

The New Zealand model for estuarine benthic species by Hayward et al. (1999) is comparable to the distribution of species within the Settlers Reserve area of the Avon-

Heathcote Estuary. The following section discusses the similarities and differences between the New Zealand wide model and the Settlers Reserve model from this study.

6.1.3.1 Species Associations

Species associations, described in Chapter 4, are similar to those determined by Hayward et al., (1999), but not all New Zealand associations are found in the Settlers Reserve area. While there are ten species associations linked with brackish estuaries, inlets and harbours in New Zealand, there are only four definitive species associations in Settlers Reserve. The main difference between the New Zealand model and the Settlers Reserve distribution is the absence of the species associations linked with the fresh water interface and marine water interface, neither of the two extremes are represented by species distribution in the Settlers Reserve area.

In the New Zealand model at the fresh-brackish water interface the *Trochammina salsa* species association is the dominant species association. This species association is not found in the Settlers Reserve area, although this species is present in low quantities along the Settlers Reserve Transect. The lack of this species association is likely because the study area does not extend far enough up the Heathcote River where *T. salsa* would be more dominant due to the extremely low salinity environment. Conversely, along the saline-brackish water interface the New Zealand model shows five species associations that are not present along the SRT, probably due to the study area not extending into the middle reaches of the Avon-Heathcote Estuary.

All of species associations from this study correlate to a similar species association described by Hayward et al., (1999). *Trochammina inflata*, *Entzia macrescens*, *Haplophragmoides wilberti* and *Miliammina fusca* species associations are largely similar when comparing habitat, tidal level, diversity, ecological habitat and major faunal associations.

A point of difference between the New Zealand model and the Settlers Reserve Transect is size of the area two of the species association are distributed in. The *Haplophragmoides wilberti* species association covers a much larger environment in the New Zealand model than it covers in this study where it is only present in one sample at 55 m. *Trochammina inflata*, however, covers a larger area than pictured in the New Zealand model covering much of the area between 5 m and 50 m. These differences are likely because the New Zealand model is generalised to take into account different brackish foraminiferal

environments from around the entire country while this study only uses the detailed sampling of one estuarine environment. The New Zealand model is unlikely to represent all brackish environments accurately so variance from this model is expected.

6.1.3.2 Diversity

Trends of diversity in brackish environments discussed by Hayward et al., (1999) do not match all the trends seen along Settlers Reserve Transect. Brackish water species diversity, in Hayward's New Zealand model, increases towards the centre of the estuary. Diversity in Settlers Reserve is represented by a bell curve with increasing species diversity over the first half of the SRT followed by decreasing species diversity over the second half of the transect (see Section 4.1.6). This is likely because this study is restricted to the upper reaches of the Avon-Heathcote Estuary at the mouth of the Heathcote River and does not extend out into the middle of the estuary. This means that large channels, the tidal mud flats and the mouth of the AHE were not sampled so diversity cannot be directly compared.

Diversity is low throughout the Settlers Reserve area and the same trend is described in the research by Hayward et al., (1999). Low diversity in brackish areas is likely due to the stressed conditions faced by the foraminifera; salinity changes constantly with the tides and in many areas benthic foraminifera are exposed to both submerged (high tide) and terrestrial (low tide) conditions (Schafer et al. 1991).

6.1.3.3 Species Distribution

As the distance from shore increases calcareous foraminifera become the dominant species in the New Zealand model as shown by Hayward et al., (1999). In this study calcareous foraminifera never become dominant species along the Settlers Reserve Transect, they appear for the first time at 55 m and appear in low percentages in samples along the remainder of the transect. These differences are due to the small area of Settlers Reserve and the study not extending further into the estuary where calcareous species are likely to be found. Calcareous foraminifera in the Avon-Heathcote Estuary as described in Pearson (2009) do appear as dominant species towards the more central areas of the Estuary.

6.1.3.4 Summary

The New Zealand wide estuarine model covers all environments while this study only covers one. The New Zealand wide model is too general to enable direct comparison as it includes a wide range of variation with all possible variables such as sediment size, salinities and pH included in description. The model from this study is able to be more specific due to

being based on a singular field area. Although specific comparisons are hard to make, generally the Settlers Reserve area foraminifera distribution fits into the New Zealand wide model distribution of brackish foraminifera with the dominant species represented in similar environments.

6.2 Core

A major aim of this study was to apply the distribution of modern foraminifera to faunas present in a core to determine the development of the southern Avon-Heathcote Estuary and identify any historic coseismic deformation events. Results for the core collected at Settlers Reserve were presented in Chapter 5 and this section discusses the significance of these findings.

6.2.1 Age Model

In order to investigate the development of the AHE and to identify coseismic deformation events, two dating techniques were used on the Settlers Reserve Core. The methods used were trace metal/isotope analysis and radiocarbon dating, as presented in results Sections 5.1, 5.5, 5.7, respectively.

6.2.1.1 Trace Metal Dating and Isotopes

A spike in the concentration of a number of trace metals occurs at around the 1.15 m mark (Cu, Zn, Ar, Ni, Sb, Pb, Co, Cr, V), and is correlated with the introduction of industrialisation in Christchurch (c. 1860) (Figure 6.1) and the runoff of associated industrial waste into the Heathcote River and its tributaries. While the manganese and iron concentrations show a spike at the 1.15 m mark this may be the result of natural processes due to these trace metals having both natural and anthropogenic sources. The most likely natural source is the eroding basaltic volcanic rocks of the Port Hills which boarder the AHE on the southern side.

The decline of industrial activity is also shown in a number of trace metals as various factories closed down and more environmentally friendly facilities were constructed. A major example of this would be the construction of the Woolston Industrial Sewer which redirected industrial waste to the Christchurch Drainage Board Treatment Plant. This opened in 1971 and by 1973 all but one remaining effluent discharging factory was redirected. All trace metals show different peaks and troughs throughout the core making it difficult to identify further dates within the core, however, at a depth of 0.15 m every trace metal, with the

exception of silver, declines rapidly. This sharp decline in trace metal concentrations could be because the grainsize increases to medium sand at this point..

The grainsize of the sediment disrupts the interpretation of the concentrations of the trace metals detected. Silt and clay have large surface areas and thus heavy metals are able to be adsorbed onto the surface of these sediments easily. Sand, however, has a much smaller surface area and the sediments are more porous which does not lead to an ideal surface to encapsulate the heavy metals in (Foerstner & Salomons 1980). This is best seen at the top of the core where sand is the dominant grainsize, below 0.07 m all but two trace metals significantly decrease in concentration. This is also demonstrated between 0.85 m and 0.35 m where silt is the dominant grainsize and almost all trace metals increase to their highest concentrations within this zone. This could be a combination of grainsize and heavy industry occurring simultaneously or results may be skewed by the fine grainsize.

The isotope data confirms the trace metal results, the carbon and nitrogen content follows the same trend as the majority of the trace metals. The trend is the concentrations increasing up the core from around 1.15 m and then decreasing quickly over the final 0.075 m as a result of the increased pollutants from anthropogenic sources. The $\delta^{13}\text{C}$ values become more negative the more recent the sediment were deposited showing that the sediments come from terrestrial origins which are likely due to the increased runoff caused by drainage of the Christchurch area and industrial waste. The $\delta^{13}\text{C}$ signature of marine sediments ranges between -20 and -22 ‰ while the $\delta^{13}\text{C}$ signature of estuarine sediments ranges between -24 and -26 ‰ (Yu et al. 2010). The $\delta^{13}\text{C}$ values in the core range from -24.99 and -27.84 becoming more negative progressively up the core, this indicates that the bottom of the core never reaches marine sediment. The $\delta^{13}\text{C}$ values, however, do indicate that the sediment is estuarine of origin becoming gradually more terrestrial which dates the deposition of the sediments at the bottom the core as being no more than 450 years before present (2013), or prior to the currently understood development of the Estuary.

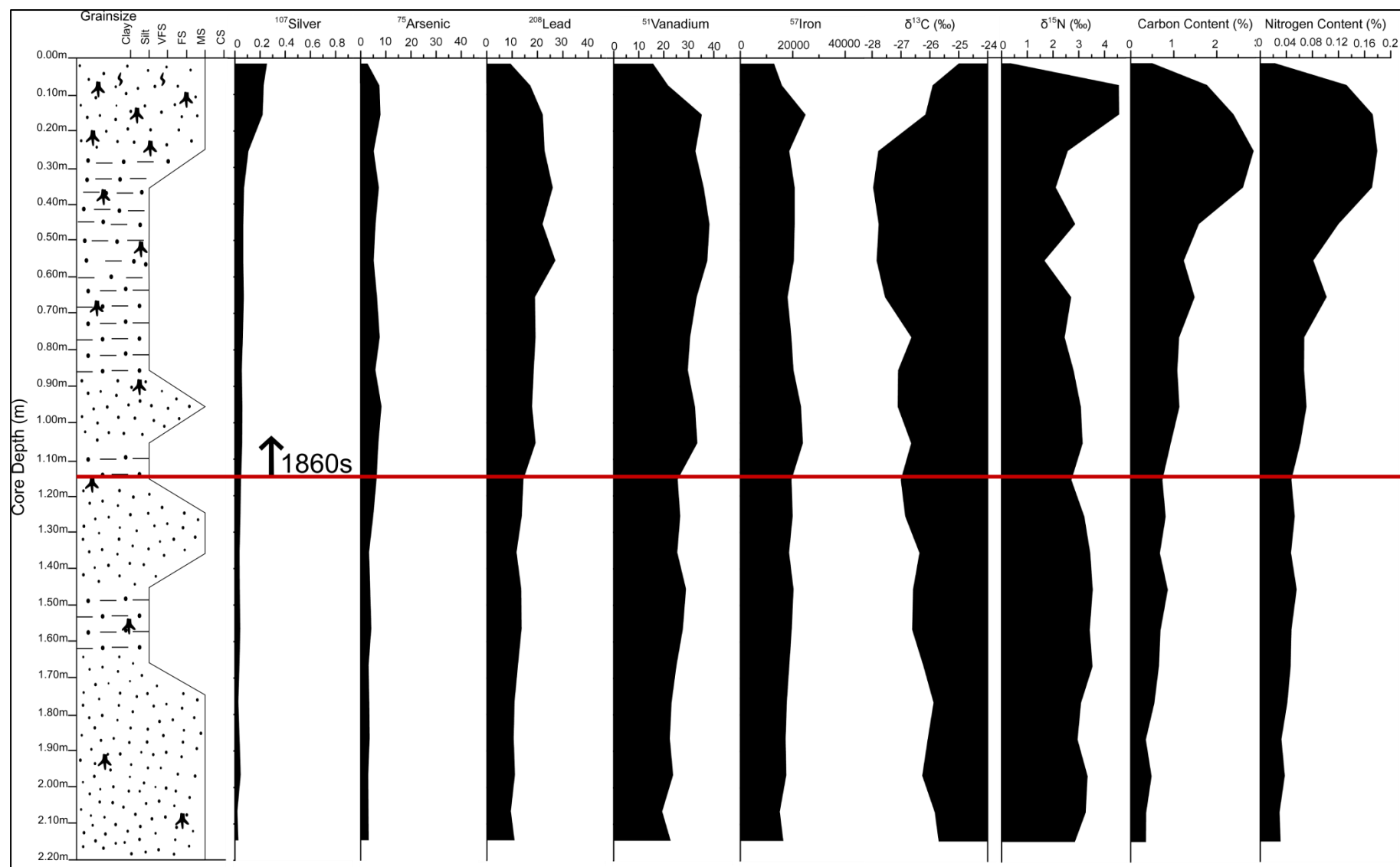


Figure 6.1 The key data used to date the core, the 1860's is identified using the core log, heavy metal concentrations and carbon and nitrogen isotopes and content percentages

6.2.1.2 Radiocarbon Dating

The dates produced by radiocarbon dating are problematic. The dates are much older than what would be expected for the depths that they were collected from. If sediment was correctly dated at 3831 ybp (2013) at a depth of 2 m then sedimentary rates would be 0.05 cm of accumulation per year which is highly unlikely. Even if sedimentation rates sped up allowing for the depth of 0.75 m to be correctly date as 311 ybp (2013) sedimentation rates would be 0.24 cm of accumulation per year which is still extremely slow for the amount of anthropogenic activity which has occurred in the area. The dated material taken at 2 m was a bulk sediment sample, this could have been tainted by carbon recycling such as coal dust contamination and does not represent the date the sediment was deposited. The dated material at 0.75 m was organic material which presented as though it was in situ with the sediment, it was thought that this material would yield an accurate date however this did not happen. Radiocarbon dating is not reliable for material post 1950's (Bowman 1990) and this would appear to be true for the plant and material dated in this study.

6.2.1.3 Dating Comparison

Dating of the core has been found to be more reliable based on trace metal and isotope analysis, although it is only possible to locate the early industrial period using this method. For the radiocarbon dates to be reliable the δC^{13} signature would have to indicate marine sediments which would be represented by less negative values than are present. As the δC^{13} signature is estuarine throughout the core the sediments must have all been deposited within the current day Avon-Heathcote Estuary, most likely within the last 450 years using current development models.

6.2.2 Foraminifera Distribution

The foraminifera present in the Settlers Reserve Core are not distributed evenly throughout the core. There are a number of possible reasons for this, these are discussed below.

Foraminifera are present in significant quantities in the top 0.25 m of the Settlers Reserve Core, the sediment is sand sized in this section of core and the majority of trace metals are decreasing overall. Between 0.25 m and 0.85 m foraminifera are present in quantities too low for assessment, the grainsize in this section of core is silt and in this section trace metals are in their highest concentrations for the entire core. Foraminifera quantities

increase again between 0.85 m and 1.35 m where the majority of sediment is sand sized and most trace metals have gradually begun increasing in concentration from background levels but have not reached their highest concentrations. The bottom of the core between 1.35 m and 2.20 m has low quantities of foraminifera, sandy sediment and low background concentrations of all trace metals. The top of this core shows that foraminifera prefer sand grainsize, as this is the grainsize the highest quantities of foraminifera were found in, however, this is contradicted at the bottom of the core. It appears likely that foraminifera prefer sediment that contains lower concentrations of heavy metal contaminants although is also contradicted at the bottom of the core.

The grainsize between 0.35 m and 0.85 m is silt sized, apart from the sample at 0.85 m all other samples taken from this section of the core contained very low quantities of foraminifera tests. The change in sediment size at this point in the core is likely due to increased sedimentation from anthropogenic sources such as, mechanical sweeping of the Heathcote River, increased industrial and household waste input and road runoff. This is also the section of the core where most trace metals (with the exception of silver) are at consistently high levels of contamination. These new increased levels of sedimentation, change in grainsize and heightened levels of heavy metals could have caused less than ideal conditions for foraminifera to live in resulting in reduced test numbers. As only one core was taken in the estuary this phenomenon cannot be compared to other areas of the Settlers Reserve area.

Between 2.20 m and 1.35 m there are very low quantities of foraminifera tests present in the core. This section of core consists of silt in the upper part and sand in the lower part. Trace metal concentrations have not yet begun increasing above background levels in this section of core and pH was not measured. To account for the lack of foraminifera in this section of core it is likely that the sandier sediments have allowed for prolonged percolation of ground water. This would increase the possibility of putting the foraminifera tests into dissolution and causing their disappearance in the core. Another possibility is that the pH levels are much lower at this depth and the sediment is anoxic causing the dissolution of the foraminifera tests that were present.

High levels of heavy metal contamination can cause a decrease in the diversity of benthic foraminifera and an increase in abundance of species with higher tolerance levels (Alve, 1995). Agglutinated benthic foraminifera species are more tolerant of higher

contamination levels and lower pH levels than calcareous forms (Alve, 1995; Jonasson & Patterson, 1992). Within the core there are three dominant species, *Trochammina inflata*, *Haplophragmoides wilberti* and *Miliammina fusca*, all three are agglutinated species and together form the dominant species in every sample. The core also contains no calcareous benthic foraminifera below the surface sample, however, there is one planktic foraminifera located at 1.35 m which is not significant as it could have been introduced via liquefied sediments from deeper down. The dominance of only three agglutinated foraminifera species and the lack of calcareous foraminifera within the core when they are present at the surface suggests that the pH of the sediment was low allowing for the dissolution of calcareous foraminifera, the pH of the core was never tested so this cannot be confirmed.

When foraminifera are exposed to highly contaminated environments many deformed foraminifera tests appear (Alve, 1995). The foraminifera in this study do not appear to show deformation of the test although the pollution of the waterways in the area is well documented. The highest levels of trace metal contamination occurs within the top 1.20 m and although heightened from background levels they may have not been at high enough levels to cause such deformation of the test.

6.2.3 Foraminifera Diversity

Diversity in the Settlers Reserve Core is low like much of that of the Settlers Reserve Transect. Diversity of the SRC was always expected to be low because of low diversity generally represented by New Zealand estuaries (Hayward et al., 1999). Due to the likely dissolution of some species, mainly calcareous, the diversity shown is not likely representative of the live assemblages. The low numbers of foraminifera in most samples is also an issue with calculating diversity, samples with as low as one and two tests can show higher diversity because there is an even number of species in the samples.

6.3 Transect – Core Comparison

One of the main reasons for collecting the Settlers Reserve Transect was to establish the current foraminiferal distribution at Settlers Reserve so that it could be compared to the foraminiferal distribution of the Settlers Reserve Core. Comparing the foraminifera distributions between the two sets of data would have enabled a model to be developed of the core showing changes in sedimentation rate and sea-level, which if these two parameters remained constant would have resulted in a linear line, however, changes in these rates occurred causing the samples to not align.

6.3.1 Interpretation of the Settlers Reserve Core Model

The tidal height model in Section 5.5 (Figure 5.10) was created in order to understand the development of the Avon-Heathcote Estuary and identify any historic coseismic deformation. The model showed a change in sedimentation rates occurring somewhere between 0.35 m and 0.85 m which was not able to be located due to low foraminiferal numbers. The samples do not plot along the trend line which represents a perfect 1 to 1 ratio indicating inconsistent rates of change. This model is recreated here in Figure 6.2 with the addition of the trace metal and radiocarbon age dates.

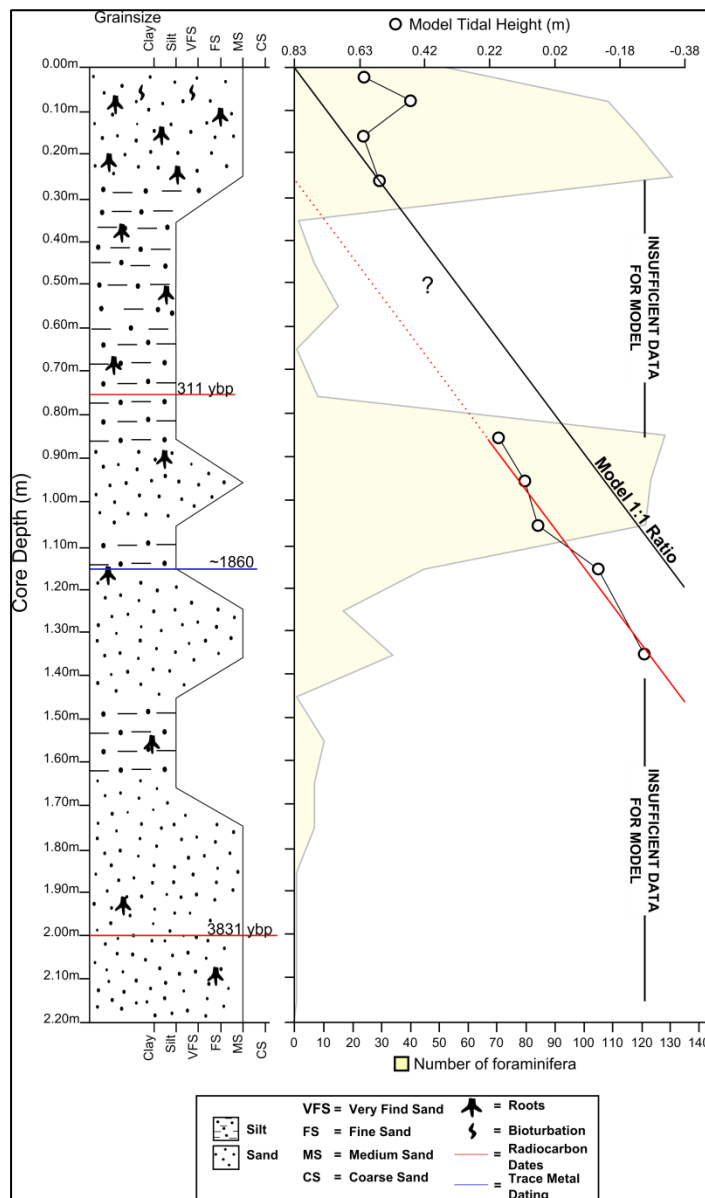


Figure 6.2 Reconstructed model of tidal heights with the addition of the age dates located

The samples from 0 to 0.35 m vary about the modelled profile. This variation does not mean that there was a change in sedimentation rates but is probably an effect of recent

physical modification to the site. The area east of the core has been manually channelled; this could cause variation in flow rates and sediment settling.

There is a lack of foraminiferal data between 0.35 and 0.85 m creating a gap in the model, before this gap samples are plotting on or above the 1 to 1 ratio line but after the gap samples are plotting consistently below the line. This indicates that at least 0.22 m of relative sea level rise has occurred in the time between the deposition of 0.85 m and 0.35 m. From 0.85 m the reconstructed tidal heights are consistently plotting below the profile line, however, these do plot along a line that runs parallel to the model line indicating that this was a period of time with constant rates of sedimentation.

In order for samples to be plotting below the model line then later on the model line there are two possibilities. Firstly there were much lower sedimentation rates occurring at the time of deposition between 1.35 and 0.85 m and then sedimentation rates increased gradually. This would have shallowed the tidal profile and allowed for a tidal height increase of 0.22 m. If foraminifera were to be present in high enough quantities the species would gradually change from lower subtidal foraminifera species to higher intertidal species.

Secondly a subsidence event took place caused by the coseismic deformation of the Estuary. As coseismic deformation of the AHE took place during the 2011 February 22nd Christchurch Earthquake it is highly plausible that this happened multiple times especially given the Canterbury Region's seismic history. As the samples between 0.85 m and 1.35 m plot parallel to the original 1 to 1 ratio line this indicates that constant rates of sedimentation took place during this time period.

There are a few options as to what earthquakes could have caused such deformation in the Avon-Heathcote Estuary, these can be narrowed down by using the trace metal dating completed on the Settlers Reserve Core. Assuming that the sediment at 1.15 m was deposited during the year 1860 and sedimentation rates are constant until a depth of 0.85 m in the core then 0.30 m of sediment has to build up before the earthquake so it cannot be an earthquake soon after 1860. It also has to be an earthquake that caused strong enough ground motions in Christchurch to cause around 0.22 m of subsidence.

The 1869 Christchurch earthquake was recorded to have caused some settlement around the Heathcote River (Downes & Yetton 2012), however, if this earthquake were the cause of the 0.22 m of subsidence then the rate of sedimentation would have to be very high

(around 3.3 cm per year) which is unrealistic even with anthropological activities affecting the Heathcote River at that time. The same can be said for the 1870 Christchurch Earthquake and even the Castle Hill Earthquake in 1881.

The North Canterbury Earthquake of 1888 had a MMI of 7 in Christchurch and caused the top 8 m of the Christ Church Cathedral spire to fall off (Pettinga et al., 2001). This is an earthquake that could be capable of causing subsidence in the Avon-Heathcote Estuary although, again, when calculating the sedimentation rates they appear too high for this to be the cause.

The 1901 Cheviot Earthquake had a MMI of 7 and caused damage to buildings in Christchurch and the Christ Church Cathedral spire fall off again (Pettinga et al., 2001). The sedimentation rates are low enough for this earthquake to be considered the cause of subsidence seen at Settlers Reserve and the MMI is high enough. It is possible that this earthquake caused the subsidence seen in the Avon-Heathcote Estuary between the depths of 0.85 m and 0.35 m in the core.

The 1922 Motunau Earthquake also fits the category of having low enough sedimentation rates and a high enough MMI (6-7) (Pettinga et al., 2001) to cause subsidence at Settlers Reserve. Another possibility is that it was a combination of both the 1901 Cheviot Earthquake and the 1922 Motunau Earthquake which caused the estimated 0.22 m of subsidence between 0.85 m and 0.35 m in the Settlers Reserve Core.

Neither of these suggestions (sedimentation rates and earthquakes) can be conclusively proven correct due to such a large gap in data in the middle of the model and the lack of data below 1.35 m so the trend in the lower core can't be continued. This model is restricted in the information it can give due to the large gaps in data.

Research undertaken by Hayward et al., in prep (2014) at the northern subsided end of the Avon-Heathcote Estuary studied two cores. ²¹⁰Pb dating and foraminifera faunas in the cores suggest that there is evidence between 0.40 m and 0.45 m depth of a subsidence event which could have occurred between 1890 and 1930. This area of the AHE would have a different sedimentation rate to the area studied for this thesis so the cores might reflect different events, however, this result is similar to that found in this study.

Chapter 7 Conclusions and Future Work

7.1 Conclusions

To conclude, there was no significant change in species distribution between samples collected in June 2011 and February 2013 at Settlers Reserve and Bridge Street in the Avon-Heathcote Estuary in Christchurch New Zealand. Coseismic deformation cannot be quantified using foraminifera at this stage, however, reassessment of foraminifera in the future may show change once sufficient sediment has accumulated.

The Settlers Reserve Transect established the distribution of foraminifera in the Settlers Reserve area of the Avon-Heathcote Estuary, this was found to be broadly similar to that of the New Zealand wide model by Hayward et al. (1999).

The Settlers Reserve Core shows evidence of past coseismic deformation, although there were not enough foraminifera found in the core to create a complete model. A subsidence event is evident between 0.35 m and 1.85 m depth in the core likely caused by the 1901 Cheviot Earthquake. The reduced foraminifera quantities makes it too difficult to locate the exact place in the core where the event subsidence took place.

7.2 Future Work

Because of an apparent lack of new sediment introduced to the Avon-Heathcote Estuary this study was unable to find any changes in foraminifera distribution over the two year time period between June 2011 and February 2013. Identifying future changes needs to be undertaken again after the build-up of at least 2 cm of sediment in the AHE. With slow sedimentation rates it is likely that this study should not be commenced again for another twenty years to see significant results.

A map of the Settlers Reserve foraminifera distribution could be created if more height profiles were surveyed in the area. This would enable the tidal heights to be projected around this section of the Estuary and the foraminiferal distribution could be inferred. With only a single line profile across the whole area inferring the foraminiferal distribution would be highly inaccurate.

Diversity indices should include the Simpsons Diversity Index to be used alongside Shannon-Weiner to give it more context as to whether there is low or high diversity. This index takes into account number of species present, the number of tests present and evenness

it is widely used in studies of ecology and does not need other samples to make comparisons with. This index gives a number between zero and one from low diversity to high diversity respectively, this is easy to understand and make immediate analysis.

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Appendices

All appendices are available in electronic form

A. 2011 / 2013 Foraminifera Data

2011 Bridge Street Foraminifera – Raw and Normalised Data

2011 Settlers Reserve Foraminifera – Raw and Normalised Data

2013 Bridge Street Foraminifera – Raw and Normalised Data

2013 Settlers Reserve Foraminifera – Raw and Normalised Data

B. Settlers Reserve Transect Data

Foraminifera Settlers Reserve Transect – Raw and Normalised Data

Grainsize Settlers Reserve Transect – Raw and Normalised Data

SEM Photographs

pH Results

Salinity Results

C. Settlers Reserve Core Data

Foraminifera Settlers Reserve Core – Raw and Normalised Data

Grainsize Settlers Reserve Core – Raw and Normalised Data

Radiocarbon Dating – Laboratory Results

Trace Metal Analysis – Corrected Data

Carbon and Nitrogen Analysis